GALCIT REPORT NO.________

GUGGENHEIM AERONAUTICAL LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

REVERSED BENDING FATIGUE PROPERTIES OF 25 S-T, 75 S-T AND 76 S-T ALUMINUM ALLOYS

Thesis by

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The author is further indebted to Dr. Leo Shapiro and The Douglas Aircraft Co. for shot-peening work, and to Mr. Joe Smith of Cooperative Wind Tunnel for photographs.

SUMMARY

The problem of this investigation was to determine the effects of surface roughness and surface stressing on the reversed bending fatigue properties of 25 S-T, 75 S-T and 76 S-T aluminum alloys.

Tests were conducted in a stress range from 37,700 psi. to that stress giving a fatigue life of 500,000,000 cycles

Surface roughness was varied from five microinches to 400 microinches. Two different machining tools were used to obtain the various degrees of surface roughness: 1/8" radius tool, and a sharp pointed tool.

Surface stressing was obtained by shot peening with 0".028 diameter shot at .010/.012 A-2 intensity, and cold rolling at 100 lbs. and 200 lbs. pressure.

It was determined that fatigue life decreased as surface roughness increased in a similar manner for specimens machined with both types of tool; but that endurance limit was not affected by the sharp tool, whereas it was decreased by the 1/8" radius tool.

Shot peening increased fatigue life of 25 S-T by about 500%; it had but slight effect on 76 S-T.

Cold rolling increased fatigue life of 25 S-T and 76 S-T by about 2500%

75 S-T was neither shot peened nor cold rolled.

This work was carried out by the author at the Guggenheim Aeronautical Laboratory, California Institute of Technology under the supervision of Dr. E. E. Sechler.

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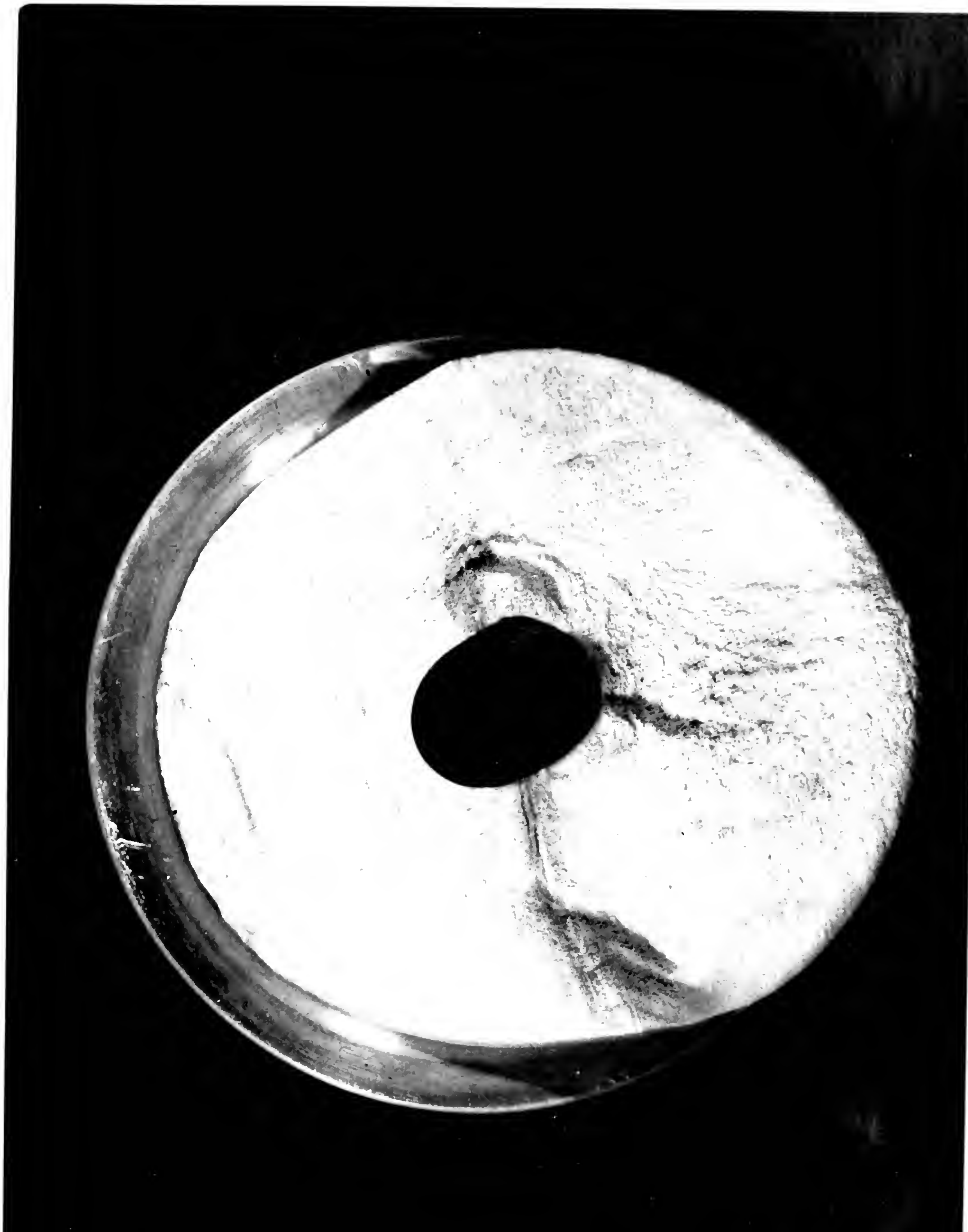
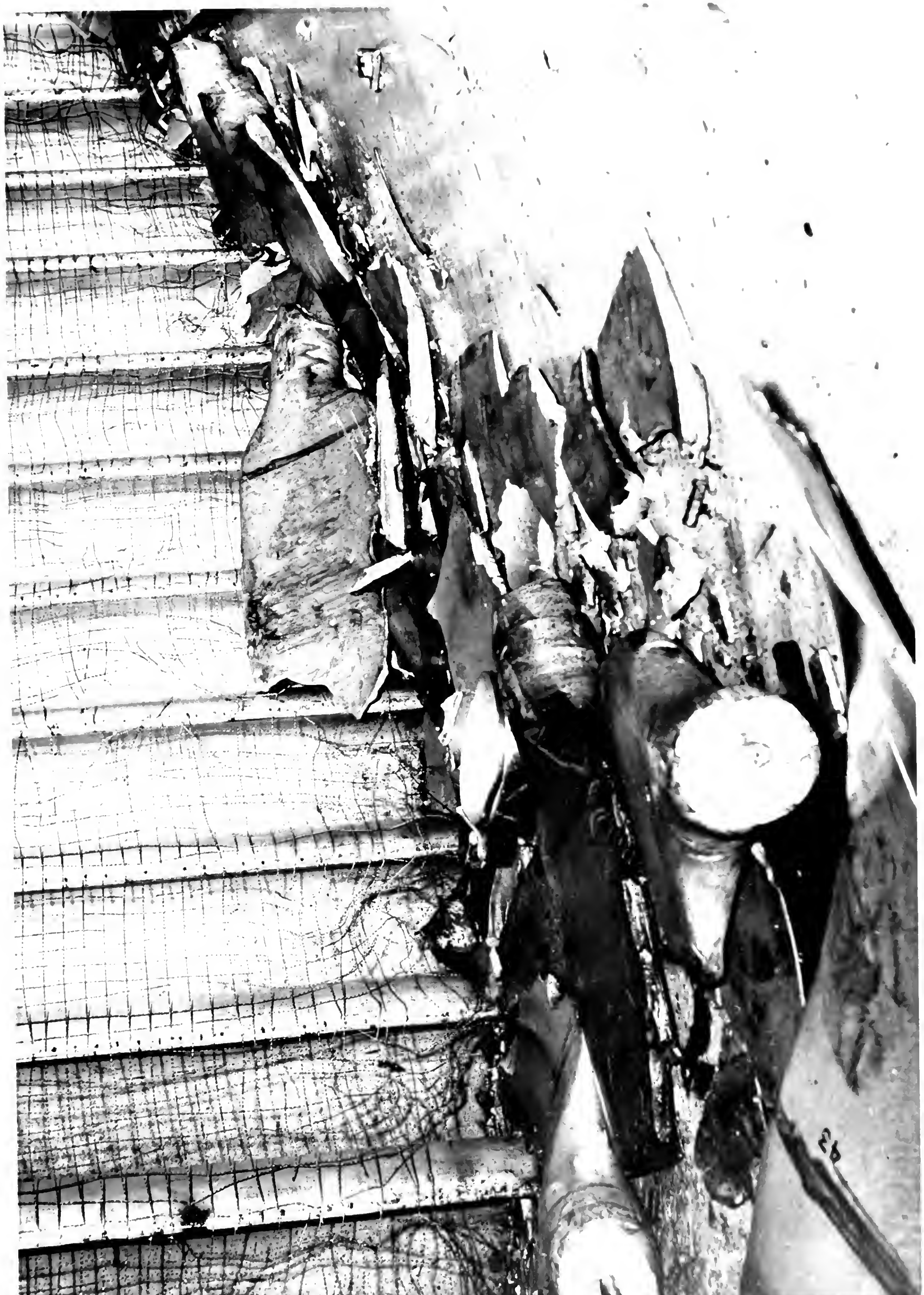


FIG. 2 END VIEW - ORIGINAL BLADE FAILURE

FIG. 3
GENERAL VIEW - PROPELLER INSTALLATION

FIG. 4
DAMAGE TO TUNNEL SHELL



I. INTRODUCTION

On the preceding pages, Fig. 1-5, one can readily see the importance and danger of fatigue failures. The installation shown is part of the Cooperative Wind Tunnel, Pasadena, California. These figures show the damage after fatigue failure of one of the propeller blades during operation. The resulting damage a mounted to about $270,000 in material, not including valuable research time and money lost while repairs were made.

This is only one example of many such failures which occur throughout industry; in the aircraft industry, especially, fatigue is of primary concern where the lightest possible parts must be made to attain the necessary requirements of low cost and high performance.

It is interesting to note here a statement of A. G. Pugsley in Ref. 1 to the effect that while the Metallurgical Science is giving us stronger and stronger alloys, there is little or no change in fatigue strength of these alloys. Therefore, it behooves the designer to pay careful attention indeed to the problem of vibration in his structure and the fatigue strength of the material with which he is working.

One very important consideration in fatigue studies is surface finish, and much research has been conducted on the effects of surface notches on fatigue strength. It was discovered that the propeller, Fig. 1., which was fabricated from 25 S-T aluminum alloy, failed at a fillet having a surface roughness of ± 100 microinches.

The necessity for more fatigue data on aircraft materials at once became apparent, especially with regard to the effects of various machining tools and finishing techniques.

This report is thus an attempt to furnish aircraft designers with additional fatigue strength data on 25 S-T, 75 S-T, and 76 S-T aluminum alloys, with particular emphasis on the effects of a) various machine surface finishes, b) shot peening, and c) cold rolling.

The investigation was conducted by the author in the Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena California under the supervision of Dr. E. E. Sechler during the period October 1948 to May 1949.

II. EQUIPMENT AND PROCEDURE

All test specimens were fabricated in the GALCIT machine shop according to the standard R.R. MOORE Specifications in Ref. 2.

The various surface finishes were machined as follows:

FEED - INCHES/REVOLUTION

	1/8" Radius Tool		Sharp Tool	
	25 S-T 75 S-T	76 S-T	25 - 75 S-T	76 S-T
5 µ	0.0015	0.0015	0.0015	Finest
50 µ	0.0160	0.0145	0.0026	0.0038
100 µ	0.0240	0.0210	0.0030	0.0046
200 µ	0.0420		0.0052	
400 µ	0.0740		0.0076	

Polishing with 600 Durite abrasive and levigated alumina followed the machining of 5µ specimens.

"µ" refers to surface roughness in microinches. The surface roughness of the specimens was checked in a Physicists Research Co. Profilometer, Type Q, Model 1, Serial No. 141.

The shot peening was done by Douglas Aircraft Co., with 0".028 diameter shot at 0.010/0.012 A 2 intensity.

In order to study the effects of surface rolling, a rolling device was designed by the author; it was built by the GALCIT machine shop and adapted to a Pratt and Whitney 13" Lathe, Model B, Serial No. 113 RB. See Figs. 6 and 7. Rolling pressures used were 100 and 200 lbs. at 0".0012/revolution feed. A constant pressure was maintained by the operator by maintaining a constant spring deflection as the rollers progressed along the test specimen. "Sample

Calculations", section VI, show computations involved in construction and use of this apparatus.

The specimens thus treated were 25 S-T and 76 S-T, machined and polished to 5 μ. Minimum diameters of these specimens were checked after rolling, and the final diameter was used in stress computations.

25 S-T specimens were made from remnants of the forging from which the propeller blade (Fig. 1) had been made. This forging came from the Chevrolet Transmission Co. and had the following properties:

Yield Strength	40000 psi
Ult. Strength	60000 psi
Elongation (2")	16.75%

Pieces cut along the long dimension of the forging were termed "with grain", those cut along the short dimension were termed "cross grain".

75 S-T specimens came from Alcoa 75 S-T6 rod, 5/8" x 12 ft. and thus were all "with grain".

76 S-T specimens were obtained from Pratt and Whitney test pieces, also "with grain".

The standard properties from A.M.S. specifications (Ref. 3) of 25 S-T, 75 S-T and 76 S-T are listed below:

	25 S-T	75 S-T	76 S-T
Yield Strength	30000 psi	72000 psi	60000 psi
Ult. Strength	55000 psi	80000 psi	70000 psi
Elongation (2")	16%	7%	14%

Specimens were placed in an optical gear tooth comparator and measurements were made of the major surface irregularities. Figs. 8 and 9 show the profiles at 100 diameters. Horizontal measurements are crest to crest; vertical measurements are crest to valley. Average values of these measurements follow:

	1/8" Radius Tool		Sharp Tool	
	Vertical	Horizontal	Vertical	Horizontal
5 μ	0	0	0	0
50 μ	0.0005	0.01480	0.0003	0.0037
100 μ	0.00065	0.02410	0.0007	0.00280
200 μ	0.0095	0.03285	0.0008	0.0054
400 μ	0.00490	0.05000	0.00140	0.00620

From these photographs it was estimated that the "sharp" tool used had a diameter at the tip of about 0.003 inches.

Tests were made in a set of four BALDWIN - SOUTHWARK R.R. MOORE FATIGUE TESTING MACHINES, Serial Nos. 265, 268, 270, and 271, running at a nominal speed of 10000 rpm. Fig. 10. The loads varied from 50 lbs. downward until a load giving fatigue life of 500,000,000 cycles was reached. All specimens were run to destruction with minor exceptions in the range above 100,000,000 cycles when it was felt that more information could be obtained by stopping and using the machine involved for other specimens.

From the data thus obtained standard σ-N curves were plotted.

The possible sources of inaccuracies or deviations from constant results are as follows:

a) Vibration of rotating parts.

b) Heating of specimen due to vibration and friction.

c) Unavoidable impacts on specimen during loading; loading was by hand.

d) Lag between loading and cycle counter setting.

e) Variation in machining.

f) Non-homogeneity of metal.

III. RESULTS AND DISCUSSION

Of utmost importance in the analysis or use of fatigue data, such as σ-N curves, is the fact that for one metal no definite σ-N curve can be obtained; instead, an area, or upper and lower bound, containing the fatigue properties is obtained. The possible errors outlined in the Introduction give adequate reasons for this situation. It is, therefore, a problem for the designer to take into account this possible variation in fatigue life of a metal at a given load.

The results of these tests have been plotted in Figs. 11 through 22 from test data obtained. On the figures where actual tests points are plotted, a dashed curve has been drawn to indicate the average σ-N line. The actual spread in the data can be seen from these figures. On figures where a group of solid curves appears, the solid curves are replots of the dashed curves of average values. All test data has been plotted.

Figures 11, 12, 13, 14, 18, and 21 show all tests of 25 S-T; Fig. 15 shows 75 S-T; Fig. 16, 17, and 22 show 76 S-T. The remaining curves Figs. 19, and 20 are comparisons of the three metals tested.

25 S-T

In general 25 S-T exhibited fairly uniform fatigue properties. Most specimens broke near the center of the test length with a break perpendicular to the axial center line. A typical fracture is shown in Fig. 23.

The endurance limit for 25 S-T appears to be about 18,000 psi. based on a life of 500,000,000 cycles. This agrees with specifications.

From Fig. 11A it can be seen that increasing roughness from 5 μ to 400 μ on specimens machined with the 1/8" Radius tool and cut "with grain" decreased the endurance limit from about 18,000 psi. to something under 10,000 psi. This result was to be expected.

However, when 25 S-T "with grain" was machined with a sharp tool an entirely different result was obtained as shown by Fig. 12A. In this case, increasing roughness decreased fatigue life in the high stress range but had very little effect on endurance limit; a value of about 18,000 psi. held for all surface roughness.

A similar result was obtained from 25 S-T "cross grain" tests illustrated in Figs. 13 and 14A. The 1/8" R. Tool again produced a decrease in endurance limit while the sharp tool had little effect.

A very interesting result was obtained from the tests on 25 S-T, "cross grain" sharp tool. See Fig. 14A. No attempt was made to draw curves since all data fell in one band. Apparently the effect of the grain direction counterbalanced the effect of surface finish.

Fig. 14B gives a comparison of 25 S-T, 5 μ, in the four conditions tested.

75 S-T

Tests of 75 S-T were made with specimens machined with a sharp tool only. This metal gave very uniform results with little scatter in the data, see Figs. 15. As in the case of 25 S-T similarly machined, all curves converged on an endurance limit of about 18,000 psi. Fractures were not as regular as those of 25 S-T. See Fig. 23. In the upper stress range 75 S-T had about three times the fatigue life of 25 S-T, and about one and one-half times that of 76 S-T. For comparison see Fig. 20.

76 S-T

Whereas 25 S-T and 75 S-T broke with fairly clean fractures, 76 S-T had a comparatively spectacular rupture. The breaks were very irregular, large pieces were thrown off the specimen, and there was an accompanying loud noise when rupture occurred. Fig. 23 shows a typical fracture.

The results of tests on 76 S-T machined with 1/8" Radius Tool showed fairly consistent values. See Fig. 16. It is felt that the 50 μ curve will converge at higher values of "N". Time prevented further investigation.

The endurance limit for 76 S-T machined with 1/8" Radius Tool appears to be between 19,000 psi. and 20,000 psi., or roughly 10% higher than 25 S-T and 75 S-T.

As can be seen in Figs. 17, machining 76 S-T with a sharp tool produced rather irregular results. However, there was noted a sharp rise in the endurance limit to a value of about 24,000 psi. This represents an increase of 33 1/3 percent over 25 S-T and 75 S-T. Fig. 20 shows this graphically.

Despite its irregularities 76 S-T, sharp tool, gave higher fatigue strength than 76 S-T, 1/8" Radius Tool, throughout the entire range. See Fig. 17E.

SHOT-PEENING

It has long been known that compression of the outer fibers of a structural member would increase its fatigue strength in reversed bending. Shot-peening seems to be about the simplest way of accomplishing this effect.

25 S-T 5μ "with grain" specimens responded readily to shot-peening with results as shown in Fig. 21. The increase in fatigue life in the high stress range was about 500%, although the endurance limit may not have been changed; an insufficient number of specimens were tested to determine this.

Shot-peening of 76 S-T specimens was carried out at the same intensity as that used on 25 S-T. However, there was no improvement in fatigue life over the unstressed 76 S-T. See Fig. 22. The increased surface roughness caused by shot-peening apparently offset any improvement in fatigue life due to surface stressing.

COLD ROLLING

The increased fatigue strength due to surface rolling was even more pronounced than that due to shot-peening. See Figs. 18, 21, and 22. For 25 S-T rolled at 100 lbs. pressure the increase over untreated specimens amounted to 2500% in the high stress range. It was not determined what the effect was on endurance limit.

A pressure of 100 lbs. was decidedly more effective than 200 lbs. It is felt that 100 lbs. is about the optimum pressure for 25 S-T for the roller design indicated in "Sample Calculations", Section VI.

When 76 S-T was rolled at 100 lbs. a similar improvement was noted in fatigue life. See Fig. 22. This amounted to about 3000%

in the high stress range.

Tests of cold rolled specimens not only showed greater improvement in fatigue life than did those of shot peened pieces, but also produced more uniform results. Furthermore, the design of rolling devices is not difficult. Therefore it would seem advisable to use cold rolling whenever the shape of the part lends itself to this method of surface stressing.

OVERSTRESSING

An attempt was made to determine the effects of "over-stressing" on fatigue strength. Fig. 11B indicates this. Two specimens of 25 S-T, 5 with grain were run at 35,000 psi. and 30,000 psi. respectively for 50,000 cycles. Both specimens were then run to destruction at 25,000 psi. The total number of cycles until failure occurred brought the points onto the normal curve well within the scatter band.

These results, while not conclusive, precluded further investigation along this line.

They furthermore do not substantiate Miner's Equation:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots = 1 \qquad \text{Ref. 5}$$

UNDERSTRESSING

Several specimens which had been run at a low stress for a large number of cycles were re-run at a higher stress. The data thus obtained was plotted and found to lie well within the scatter band for the particular material and test condition. These particular specimens are as follows:

Specimen	Metal	Fig.
12, 12a	25 S-T	11 D
10, 11	25 S-T	11 E
13, 13a	25 S-T	11 E
3, 5	76 S-T	16 B
5, 6	76 S-T	17 D

There was no indication that the cycles at a low stress had any effect on fatigue life at a higher stress. In other words 25 S-T and 75 S-T were not susceptible to "coaxing", nor was there any fatigue damage noted due to low stress operation. This is further refutation of Miner's Equation.

IV. CONCLUSIONS

The following conclusions may be drawn from the results obtained in this work:

1) The endurance limit of 25 S-T was verified to be 18,000 psi.
2) Machining with 1/8" radius tool severely reduces the endurance limit of 25 S-T as surface roughness is increased.
3) Machining 25 S-T with a sharp ended tool gives effects parallel to those obtained with 1/8" radius tool until a stress of about 20,000 psi. is reached. The endurance limit remains at 18,000 psi. for all surface conditions obtained with the sharp tool.
4) Shot-peening of 25 S-T with .010/.012 A-2 intensity increases fatigue life about 500% in the stress range between 40,000 psi. and 20,000 psi.
5) Cold rolling of 25 S-T at 100 lbs. increases fatigue life about 2500% in the stress range between 40,000 psi. and 25,000 psi.
6) The endurance limit of 75 S-T is about 18,000 psi.
7) 75 S-T machined with a sharp tool has about four times the fatigue strength of 25 S-T, similarly machined, in the high stress range; but it has the same endurance limit, 18,000 psi.
8) 76 S-T has a fatigue strength between 75 S-T and 25 S-T in the high stress range; but it has a higher endurance limit: 19,000 - 20,000 psi. for 1/8" R. Tool, 24,000 psi. for sharp tool.
9) The effect of shot-peening 76 S-T with .010/.012 A 2 intensity

was negligible.

10) Cold rolling 76 S-T at 100 lbs. increased fatigue life about 3000% in the high stress range.

It is recommended that future tests with these machines be conducted with the machines mounted on individual stands and in cushioned mountings. The present set-up allows vibrations from one machine to be transmitted to all the others.

It is further recommended that more tests be conducted as follows:

1) 75 S-T machined with 1/8" radius tool.

2) 75 S-T shot peened and cold rolled.

3) Complete 25 S-T and 76 S-T shot peened and cold rolled to determine effect on endurance limit.

4) Vary intensity of shot peening and rolling pressure to determine optimum values for each metal.

5) Further investigate the effects of understressing and overstressing on fatigue life.

V. REFERENCES

1. "Behaviour of Structures under Repeated Loads", Pugsley, A. G., J.R.A.S., Vol. 51, p. 715.

2. "Metals Handbook", 1948, p. 120, Fig. 3a.

3. "Aeronautical Material Specifications", 4130E, 4137, 4154C.

4. J. Apl. Mech. Vol. 57, June 1935, p. A 69-71.

5. "Experimental Verification of Cumulative Fatigue Damage", Miner, M. A. Auto. and Aviation Ind. Vol. 93, Dec. 1, 1945.

VI. SAMPLE CALCULATIONS

1. Stress Calculation:

$\sigma = \frac{16WL}{d^3}$ p.s.i. $\qquad$ d = 0".30

W = 10 lbs. (Tare) + Added Weight

= 755W p.s.i. $\qquad$ L = 4"

2. Design of Rolling Device: (See Ref. 4.)

Rollers: $\qquad$ Specimen

$r_1 = 0''.8$ $\qquad$ $r_s = 0''.015$

$r_{1s} = 0''.33$ $\qquad$ $r_{s1} = 9''.75$

$$\frac{1}{R} = \frac{1}{0.8} + \frac{1}{0.33} + \frac{1}{0.15} + \frac{1}{9.75}$$

$$= 1.25 + 3 + 6.66 + 0.102$$

$$= 11.01$$

$$R = 0.0909''$$

This value of R allows the use of the Boussinesq Formula:

$$\tau = \frac{P}{8\pi}\left[\frac{7 - 2\nu}{z^2}\right]$$

$\tau = \frac{1}{2}\, y_t$ p.s.i.

P = Force lbs.

z = Depth of penetration - inches

ν = Poisson's Ratio

Say,

$z = \frac{1}{4}$ radius of specimen

$= \frac{1}{4} \times 0.15 = 0''.0375$

$$P = \frac{8\pi z^2 \tau}{7 - 2\nu} = \frac{8\pi\,(0.375)^2\,\tau}{6.5} = 0.0054\,\tau$$

	25 S-T	75 S-T	76 S-T
yt	30,000	66,000	60,000
τ	15,000	33,000	30,000
P	81	178	162

VII. FIGURES 6-23

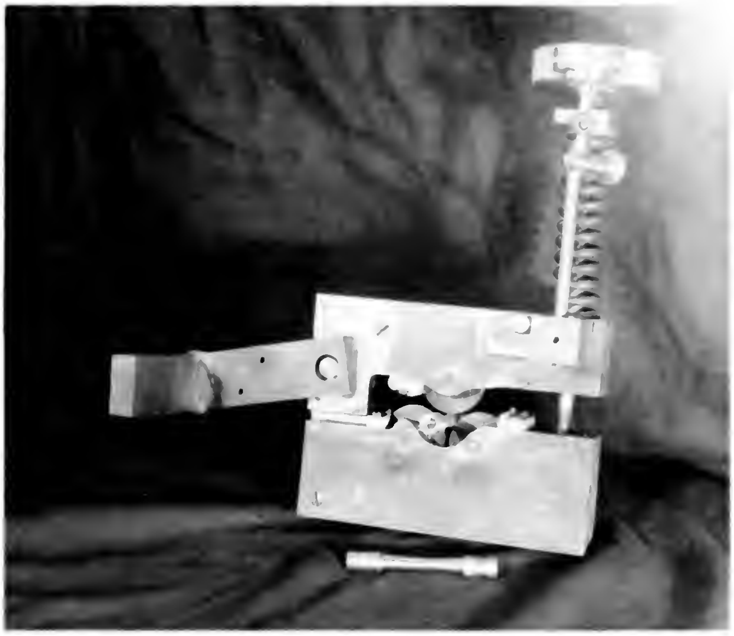


FIG. 6. ROLLING DEVICE

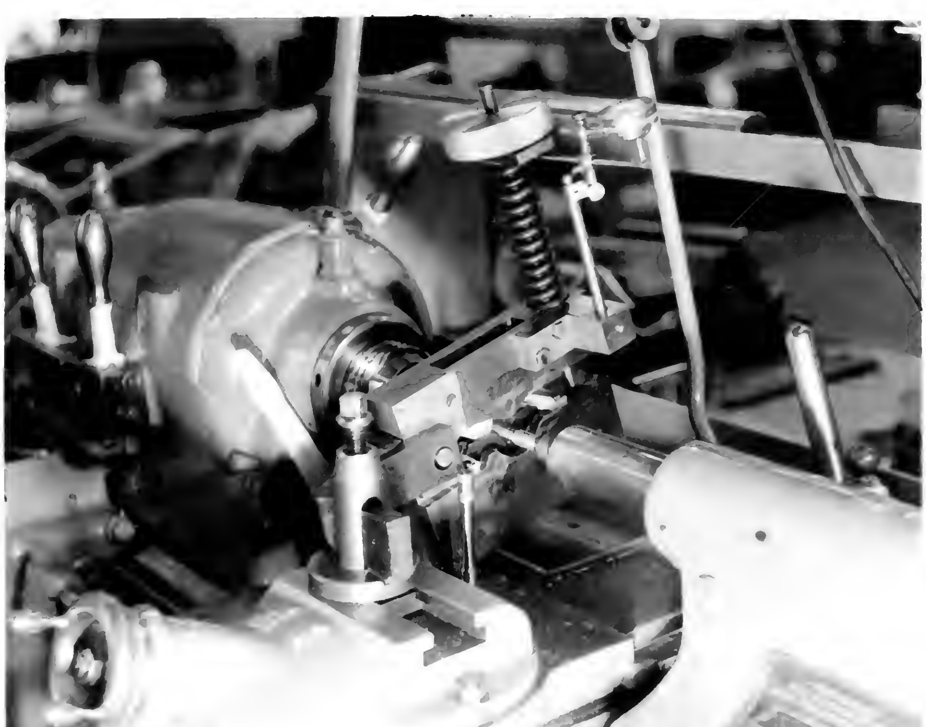


FIG. 7. ROLLING DEVICE AS USED

5 μ

50 μ

100 μ

200 μ

400 μ

FIG. 8

SURFACE PROFILES - $\frac{1}{8}$" RADIUS TOOL

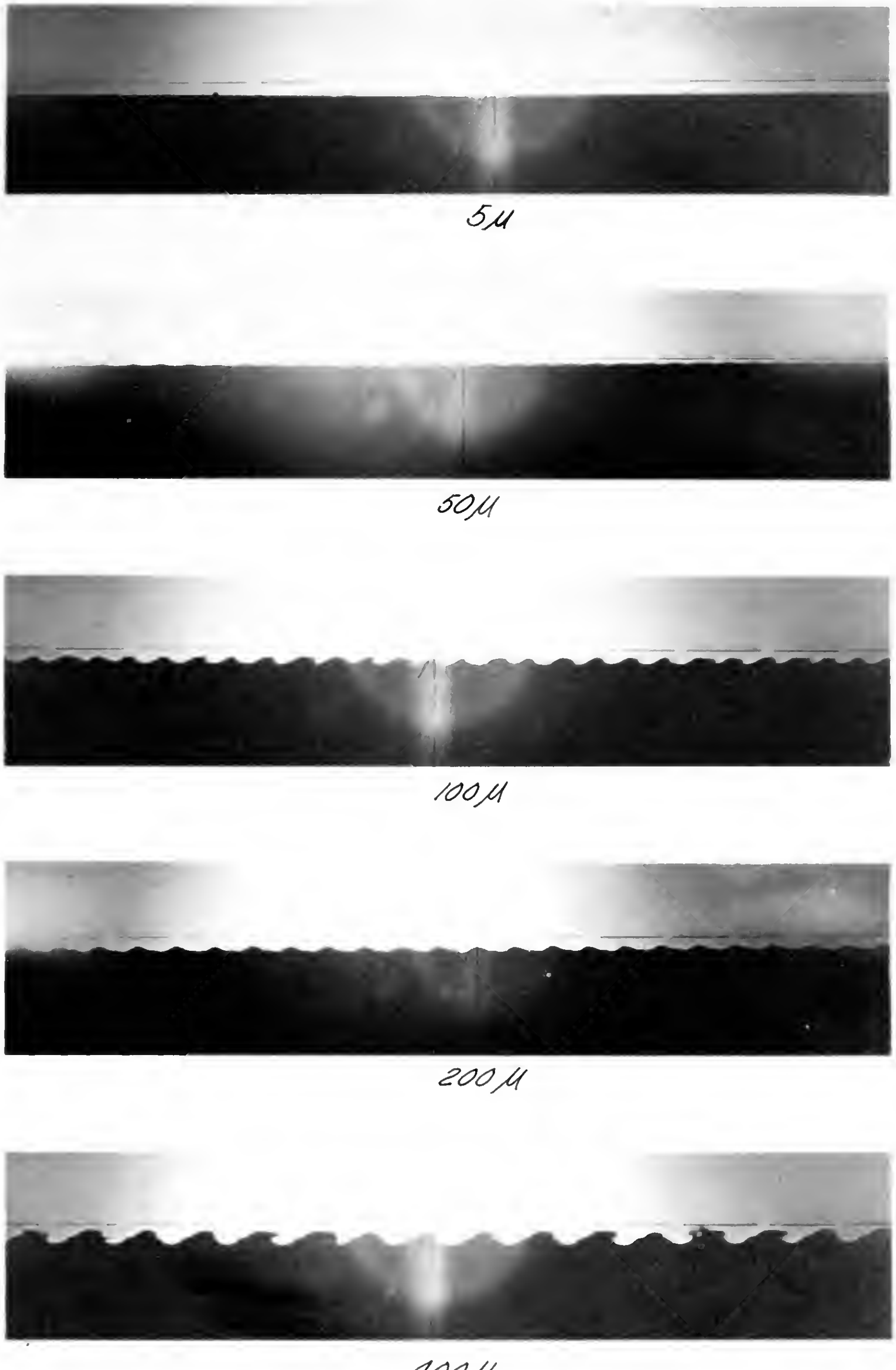


FIG. 9
SURFACE PROFILES - SHARP TOOL

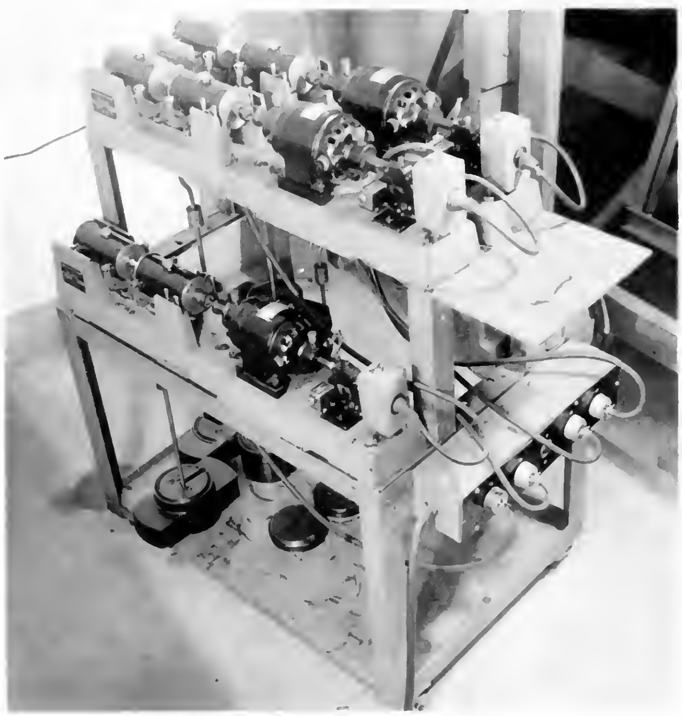
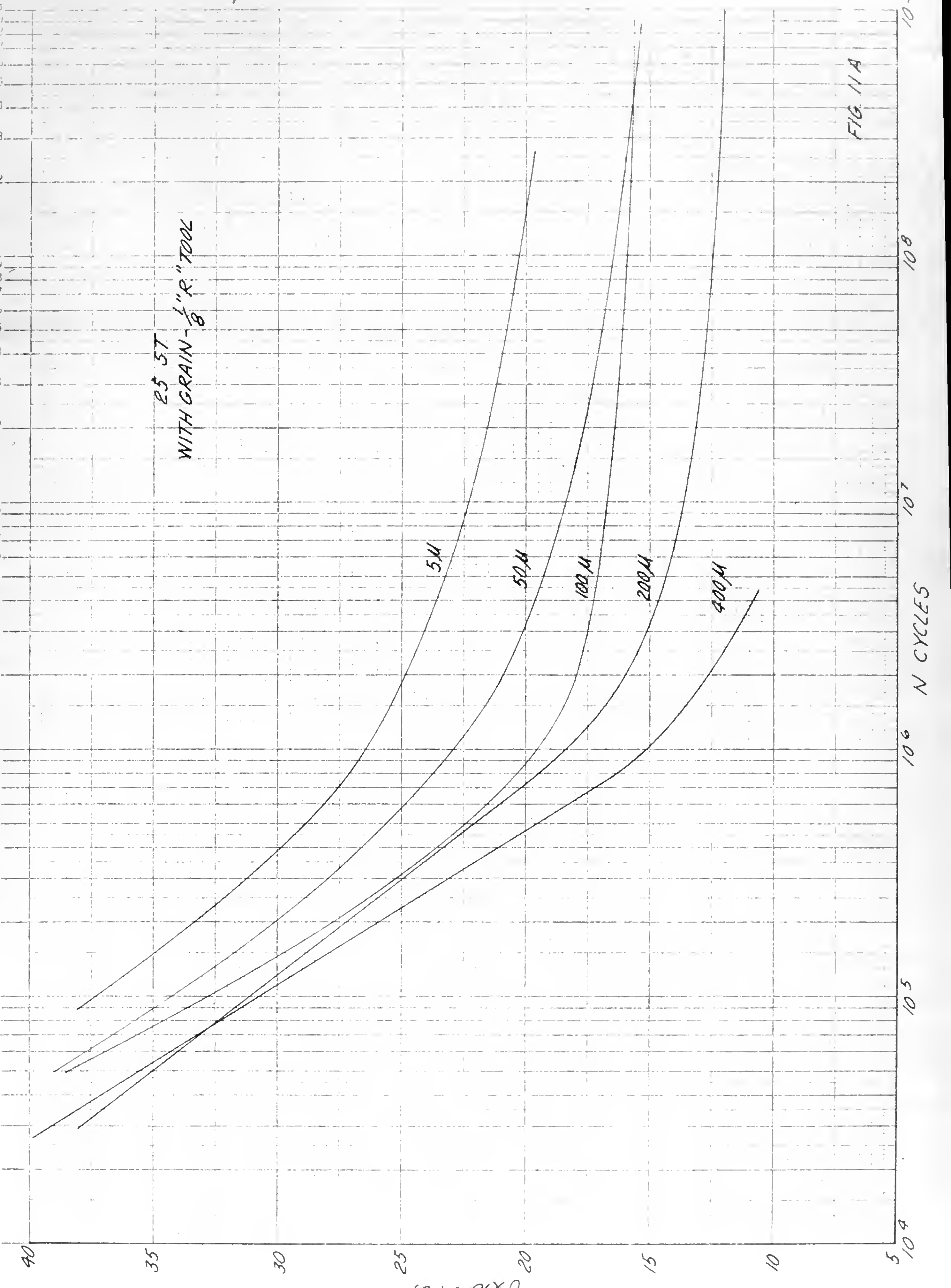


FIG. 10. TEST STAND


25 ST
WITH GRAIN - 1/8" R" TOOL
FIG. 11 A
5μ
50μ
100μ
200μ
400μ
N CYCLES
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
40
35
30
25
20
15
10
5

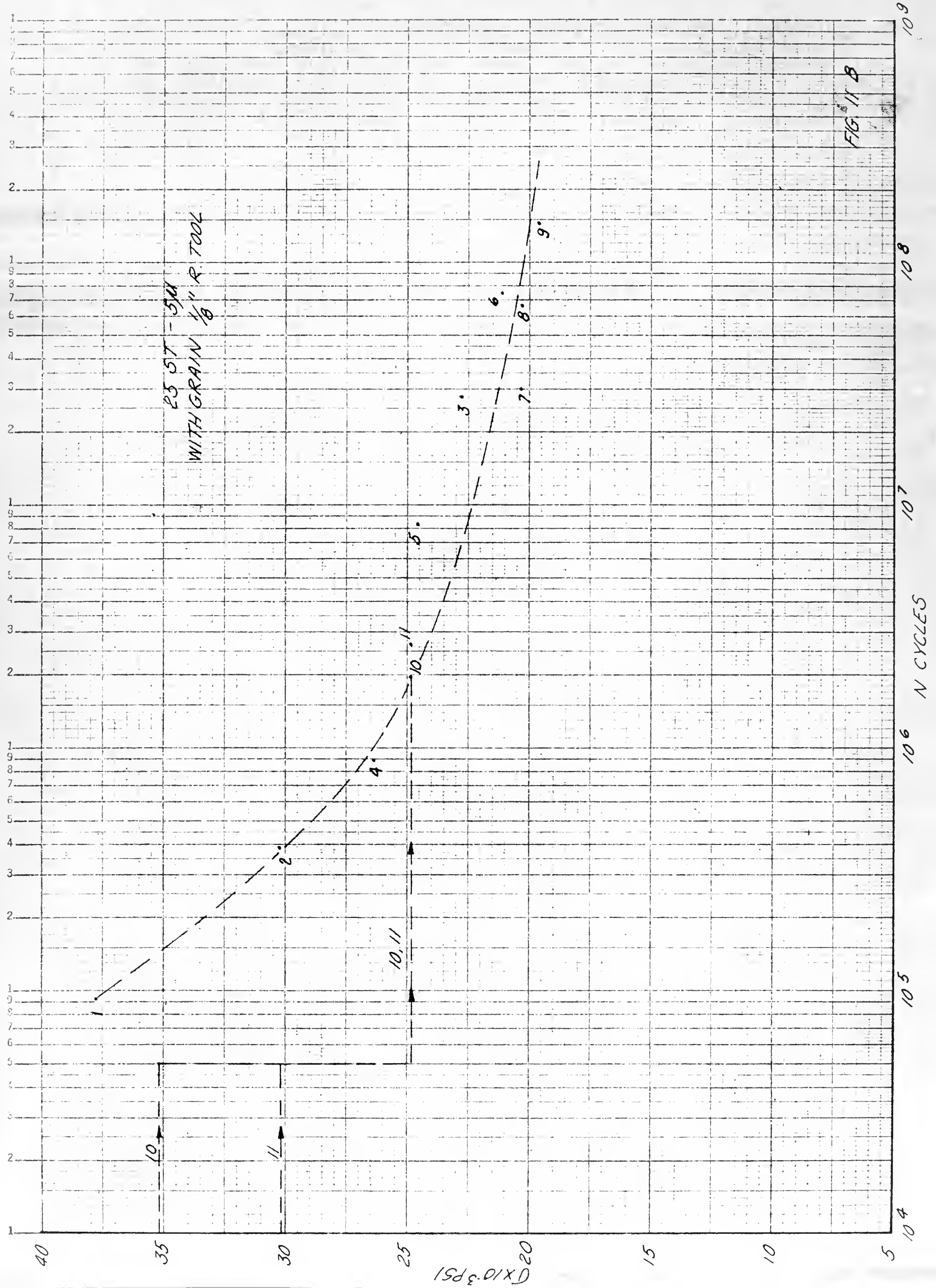
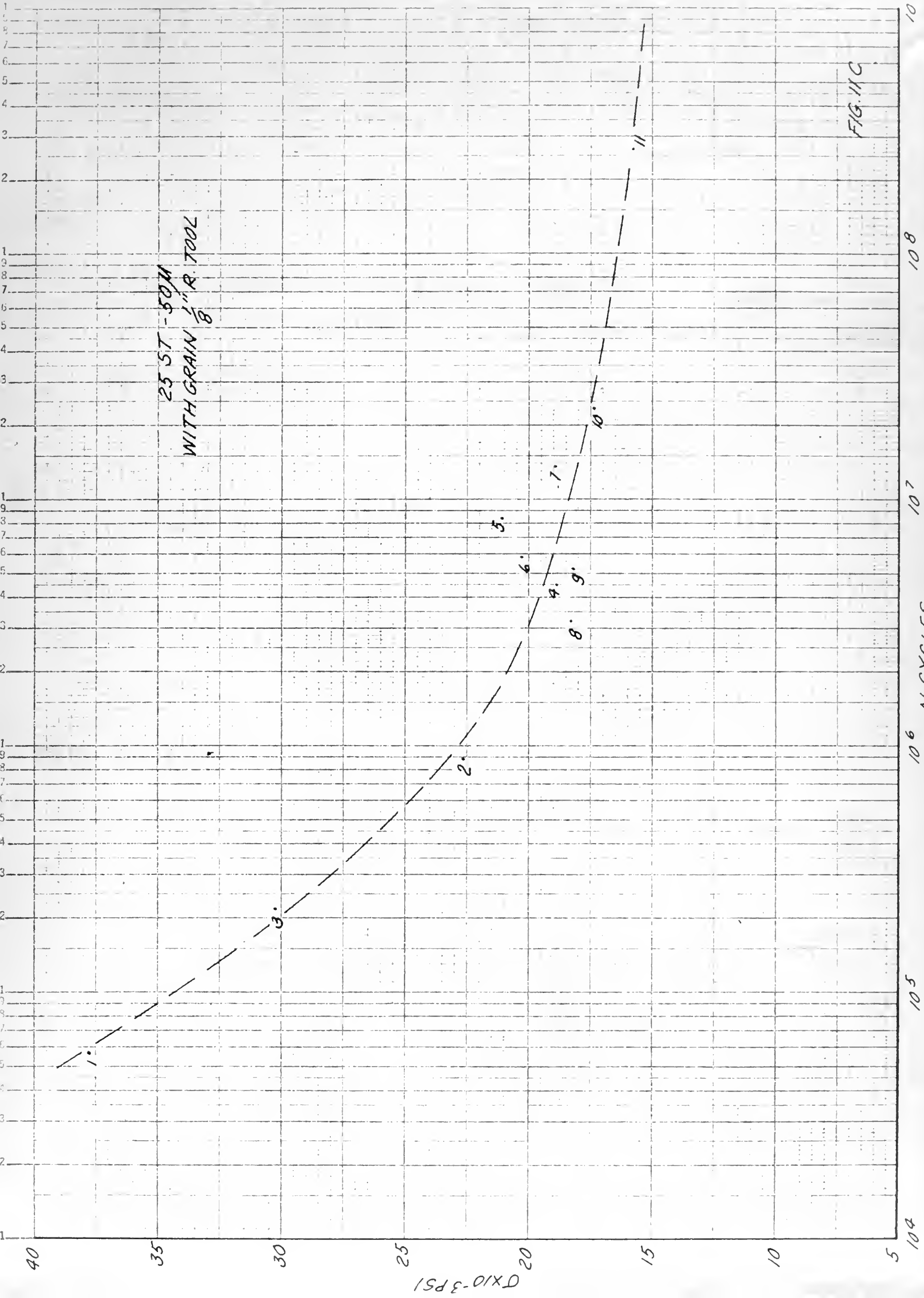


FIG. 11 B
25 ST - 5W
WITH GRAIN 1/8" R TOOL
N CYCLES
σ x10^-3 PSI
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5
10.11
10
11


25 ST-50M
WITH GRAIN 1/8" R. TOOL
FIG. 11 C
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

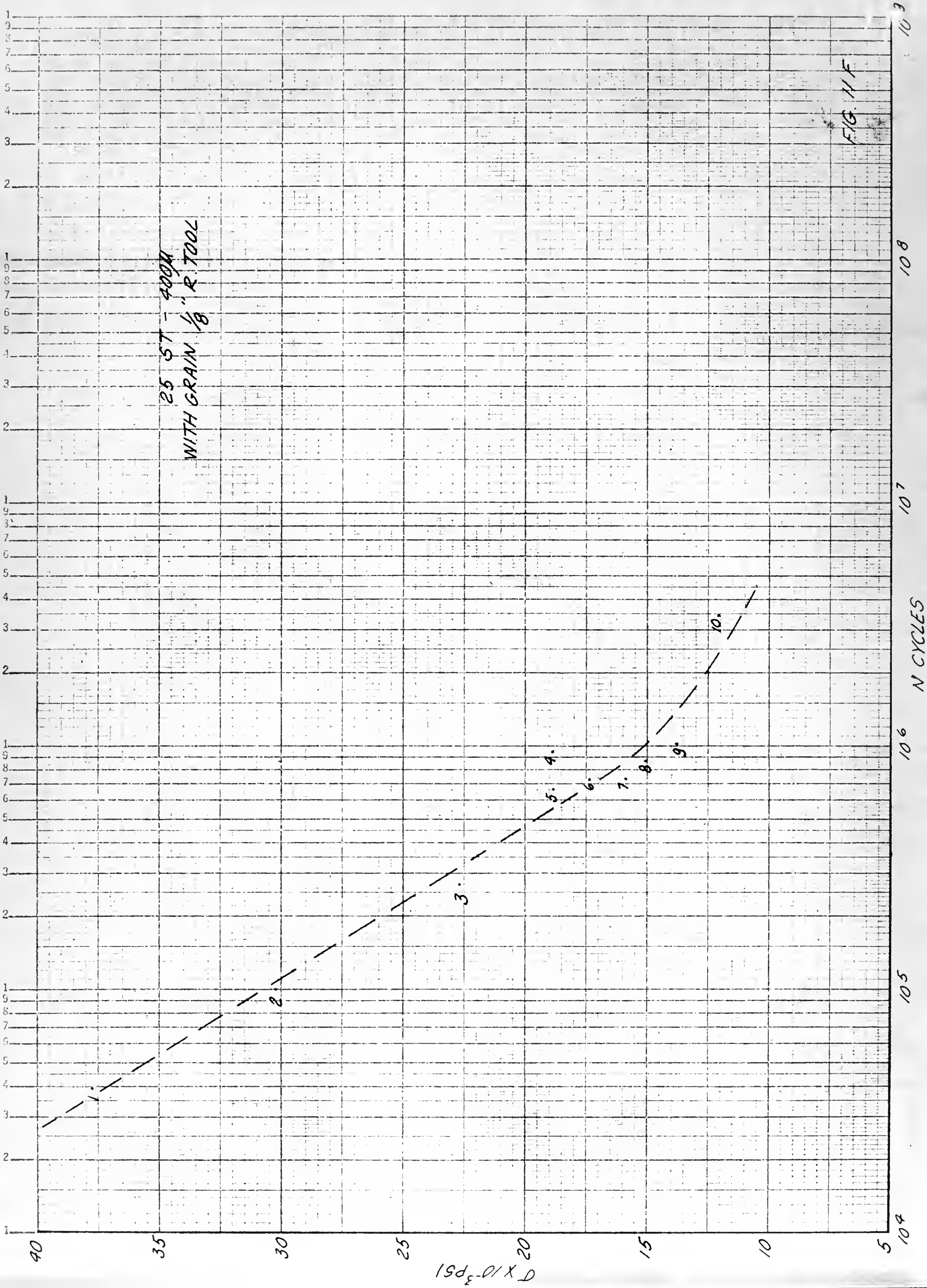

25 ST - 400μ
WITH GRAIN 1/8" R TOOL
N CYCLES
σ X 10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

FIG. 11F

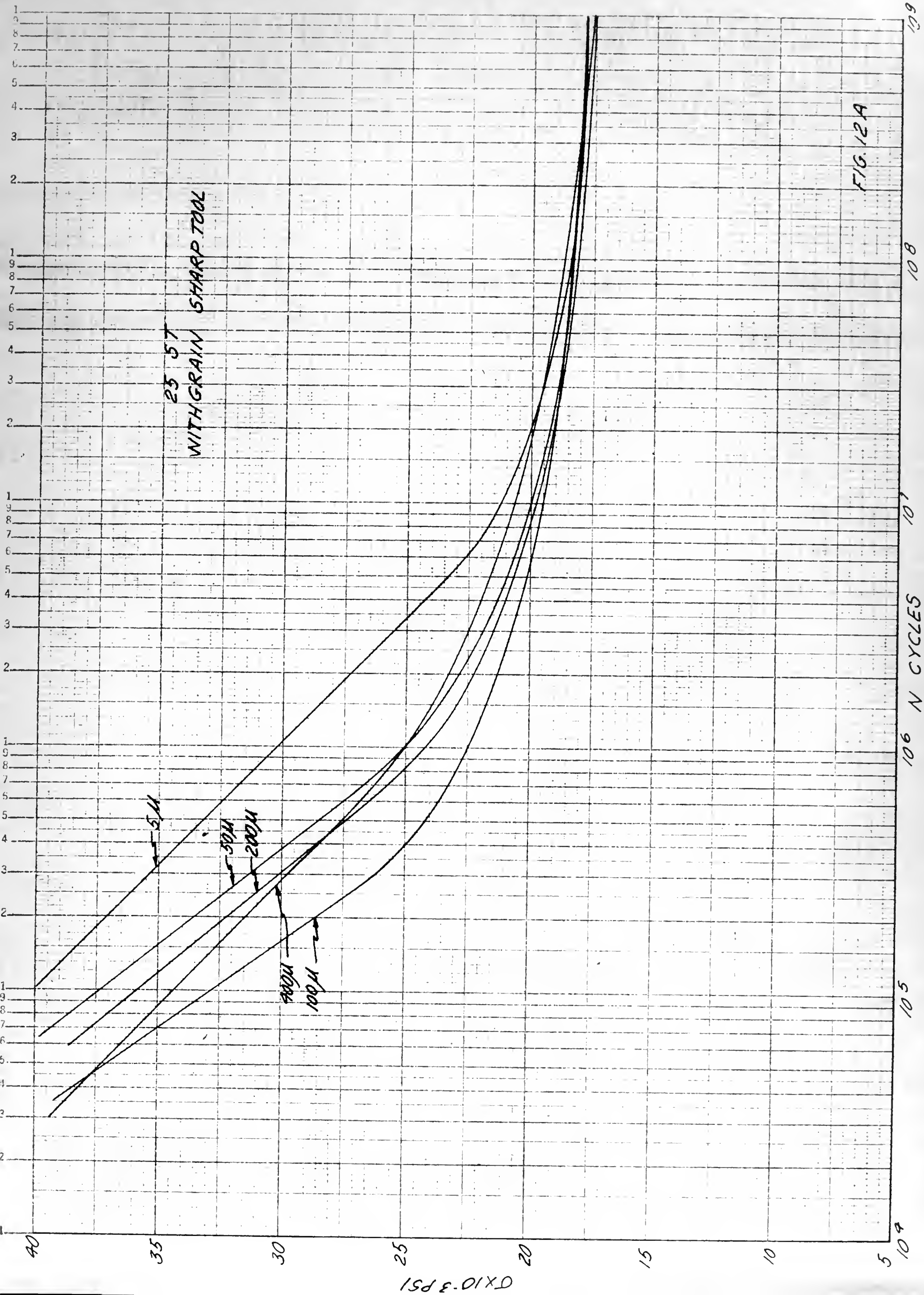
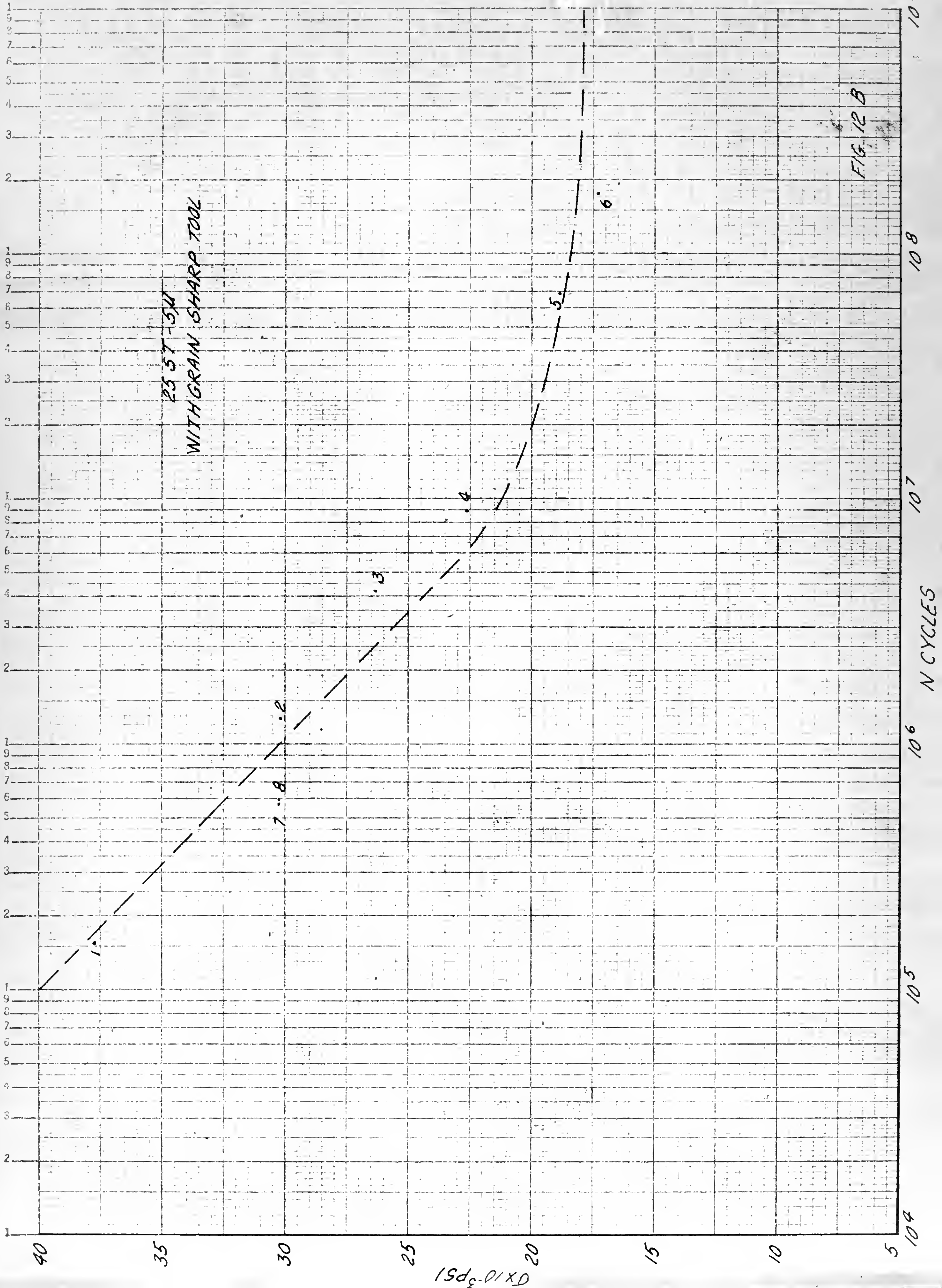

25 ST
WITH GRAIN SHARP TOOL
N CYCLES
σ x10⁻³ PSI
5μ
50μ
200μ
1000μ
100μ

FIG. 12A


25 ST-5W
WITH GRAIN SHARP TOOL
FIG. 12 B
N CYCLES
σx10⁻³ PSI
40
35
30
25
20
15
10
5
10 4
10 5
10 6
10 7
10 8
10 9

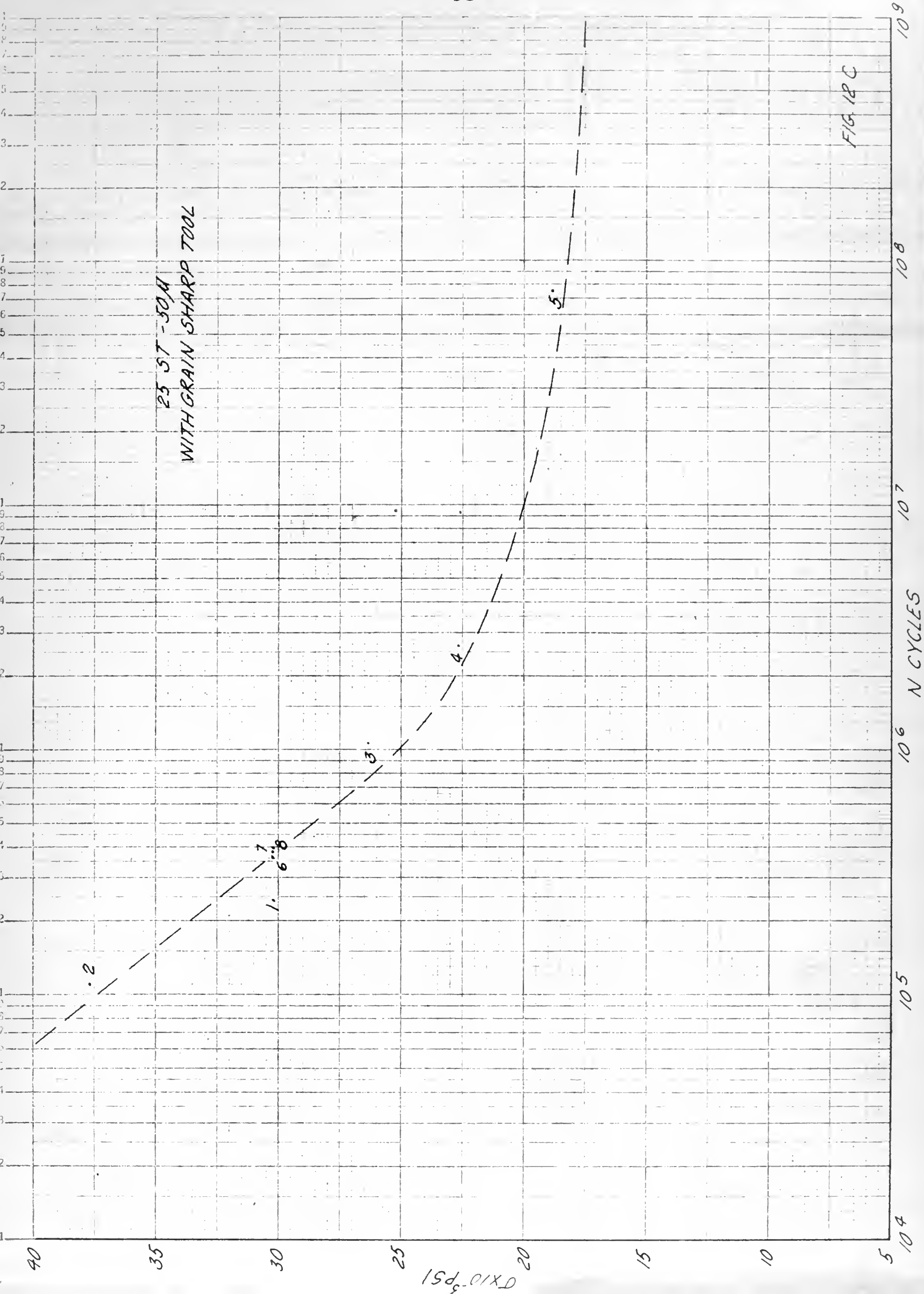


FIG 12C
25 ST-50A
WITH GRAIN SHARP TOOL
N CYCLES
$\sigma \times 10^{-3}$ psi
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

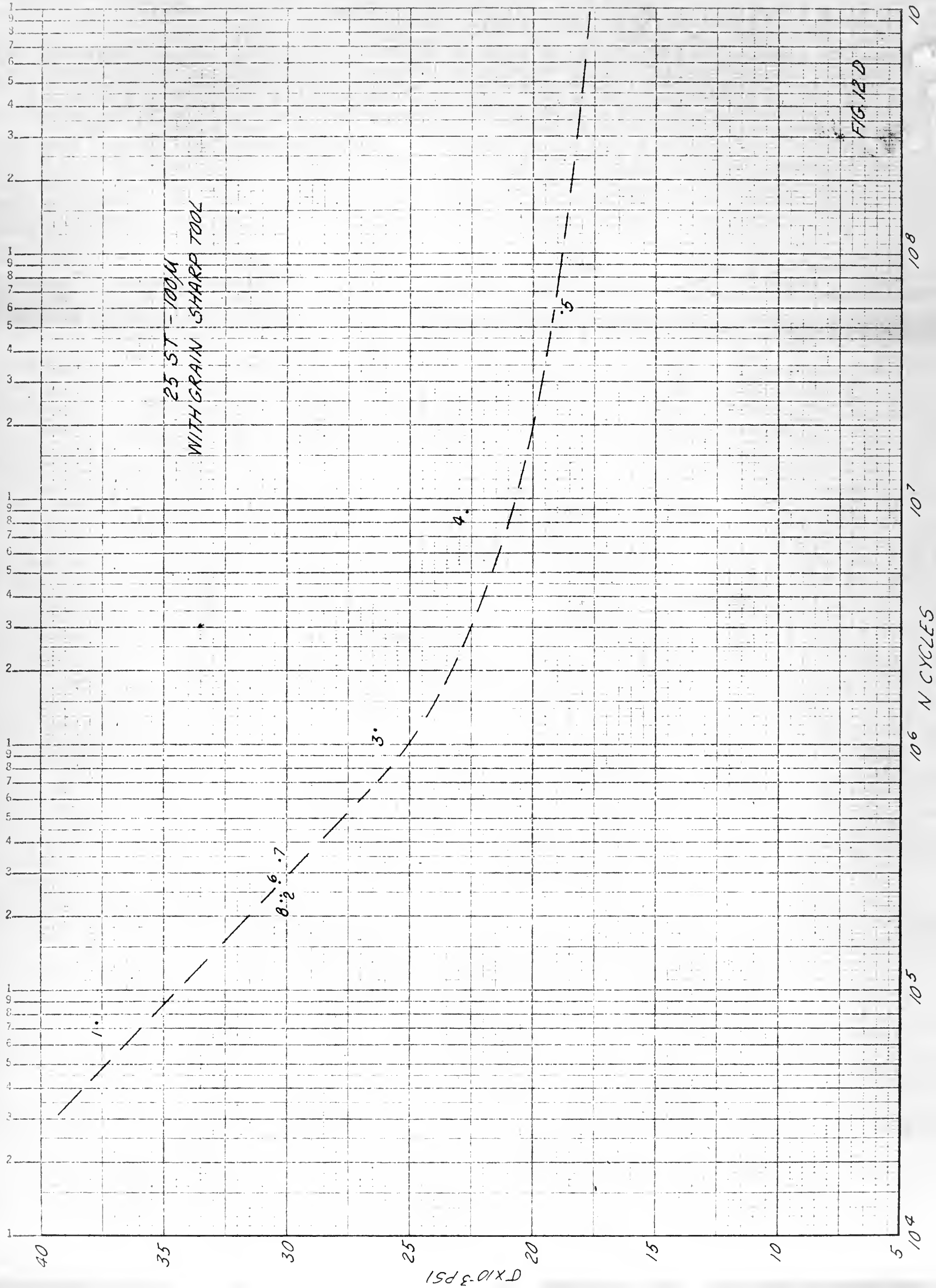


FIG 12 D
25 ST - 100μ
WITH GRAIN SHARP TOOL
N CYCLES
σ x10-3 PSI
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5

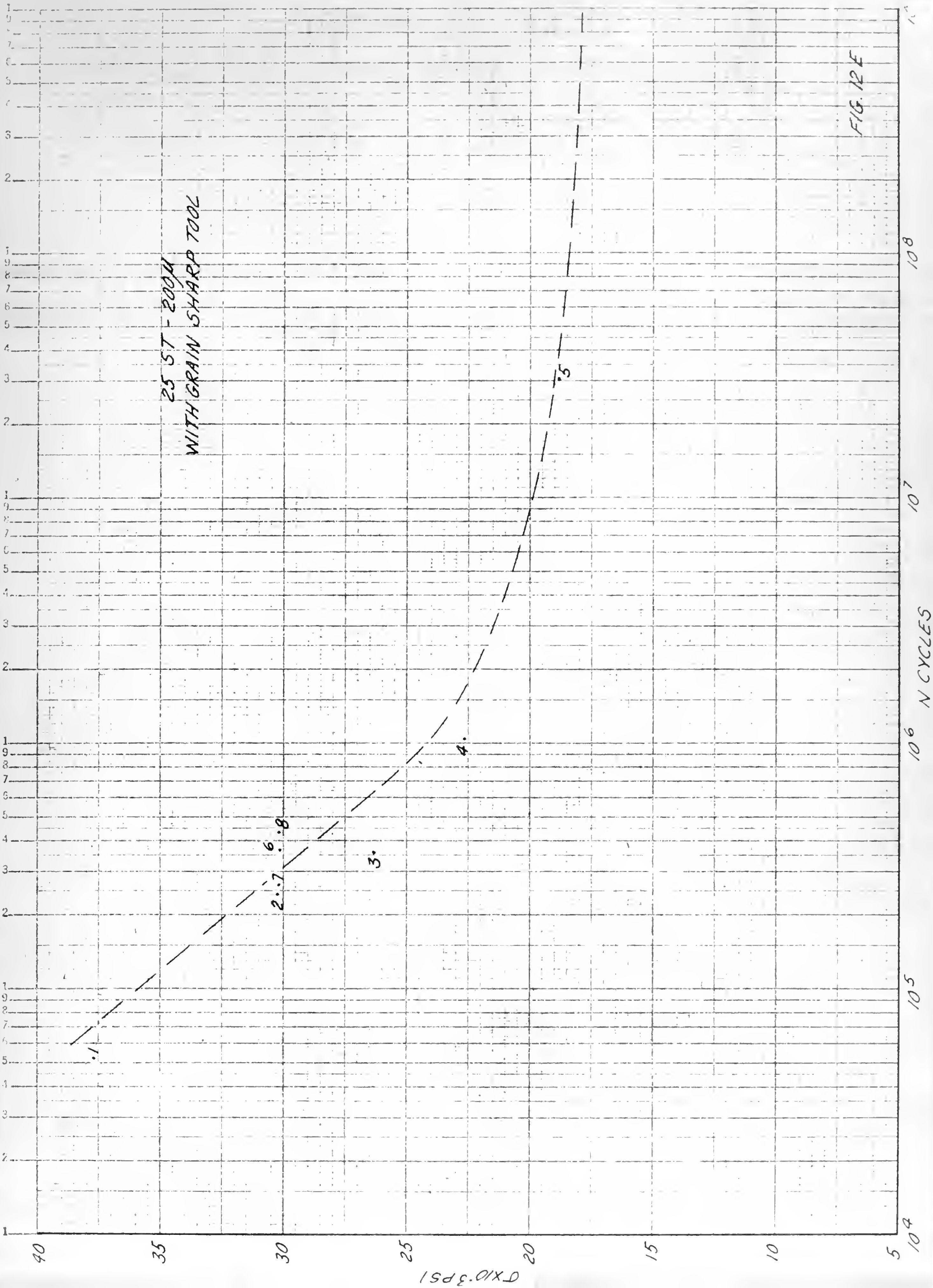

25 ST - 200μ
WITH GRAIN SHARP TOOL
N CYCLES
10^4
10^5
10^6
10^7
10^8
10^9
$\sigma \times 10^{-3}$ PSI
40
35
30
25
20
15
10
5
1
2
3
4
5
6
7
8

FIG. 12E

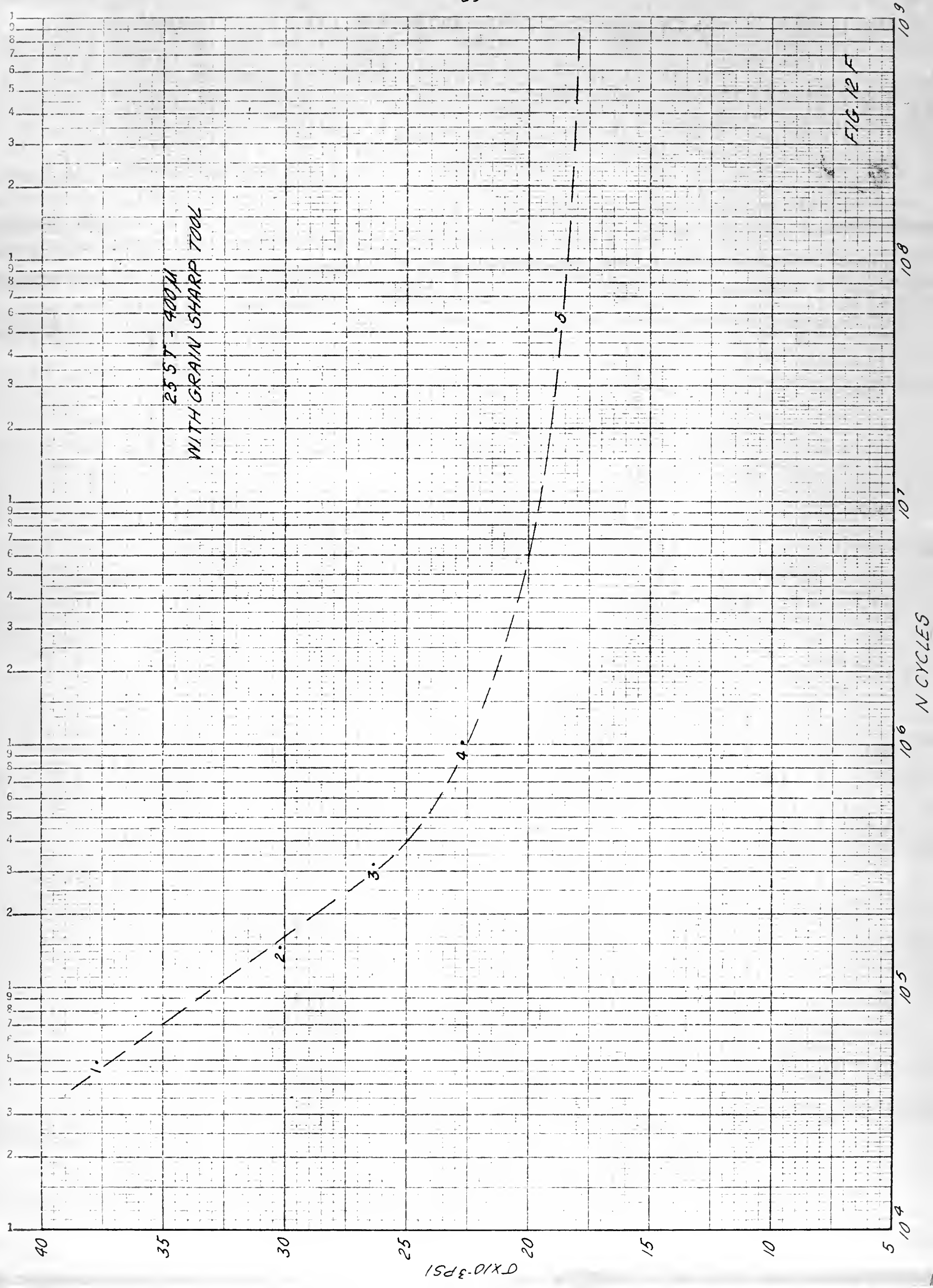


FIG. 12 F
25 ST - 400 μ
WITH GRAIN SHARP TOOL
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

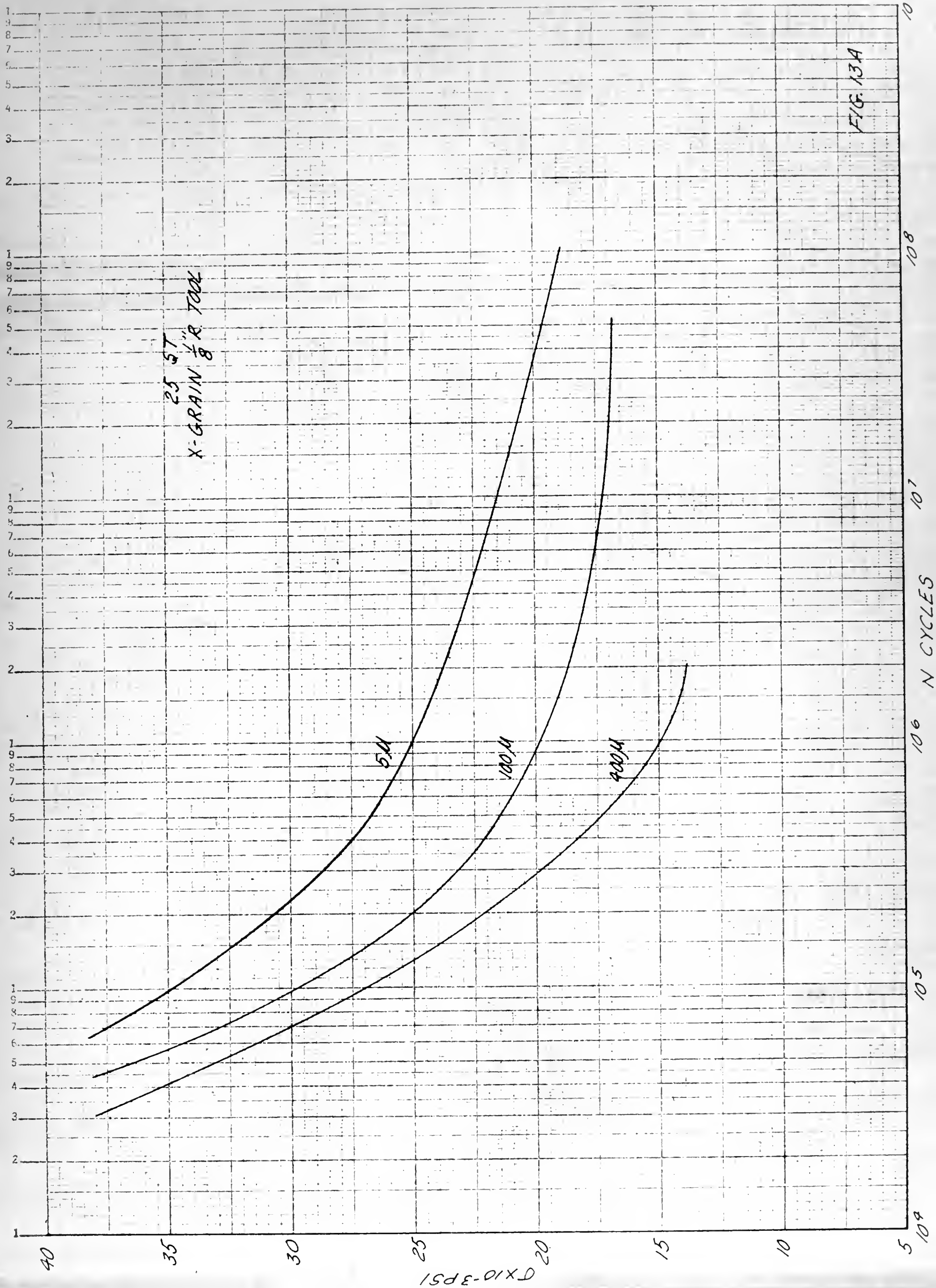

25 ST
X-GRAIN 1/8" R TOOL
5μ
100μ
400μ
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5
10^5
10^6
10^7
10^8
10^9

FIG. 13A

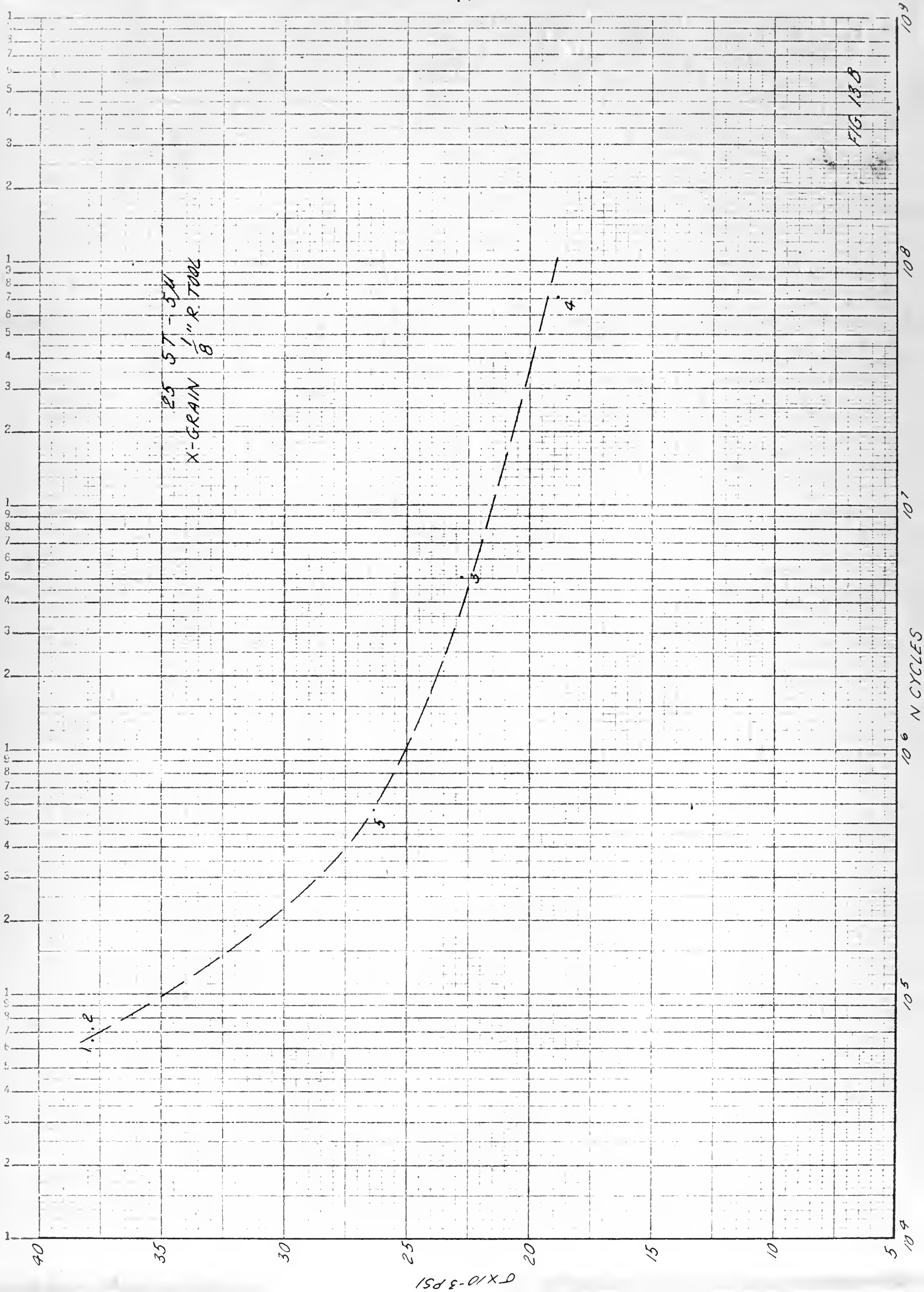


FIG 13.B
25 ST-SH
X-GRAIN 1/8" R. TOOL
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

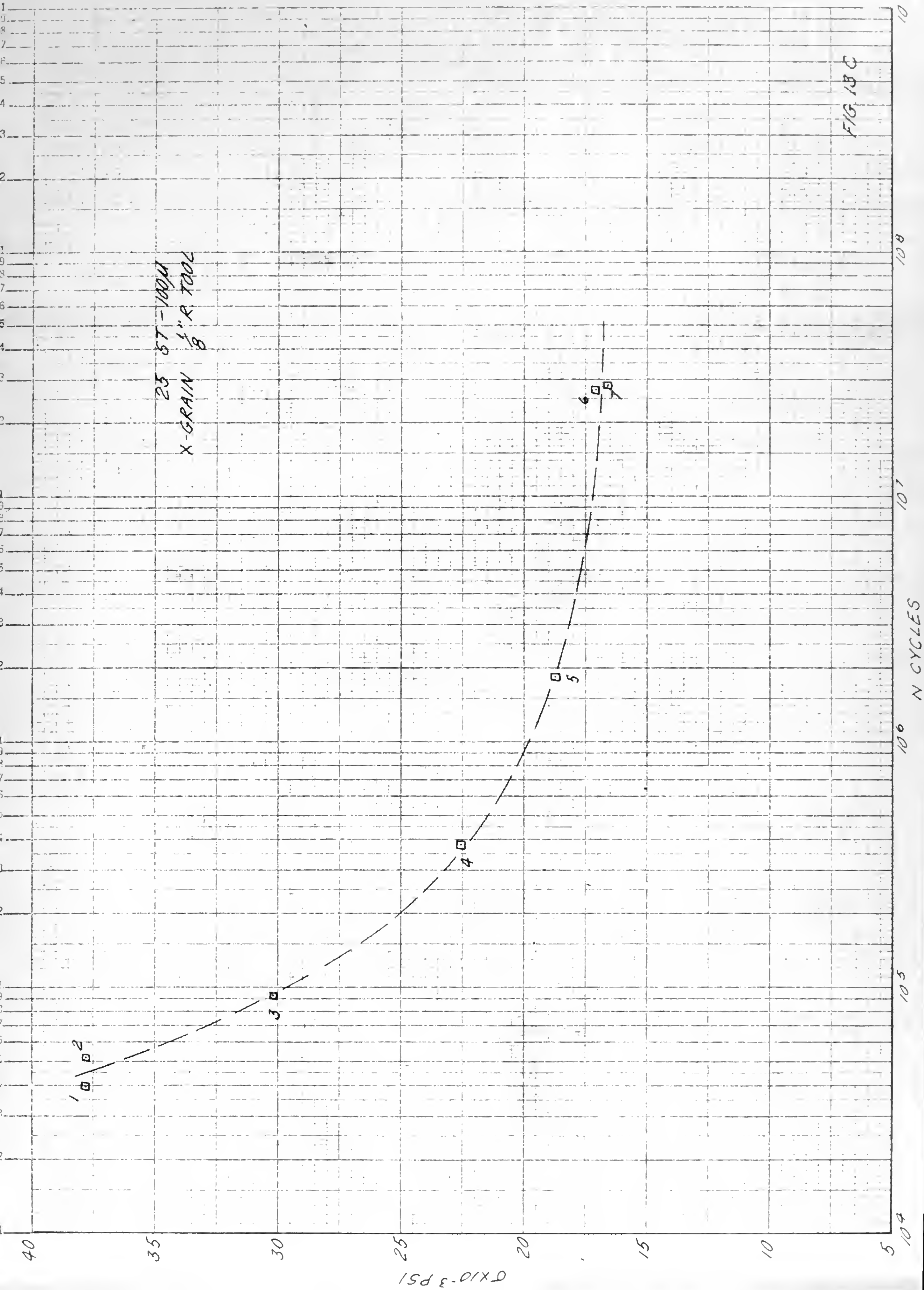


FIG 13 C
25 ST-100μ
X-GRAIN 1/8" R TOOL
N CYCLES
σ x10^-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9
1
2
3
4
5
6
7

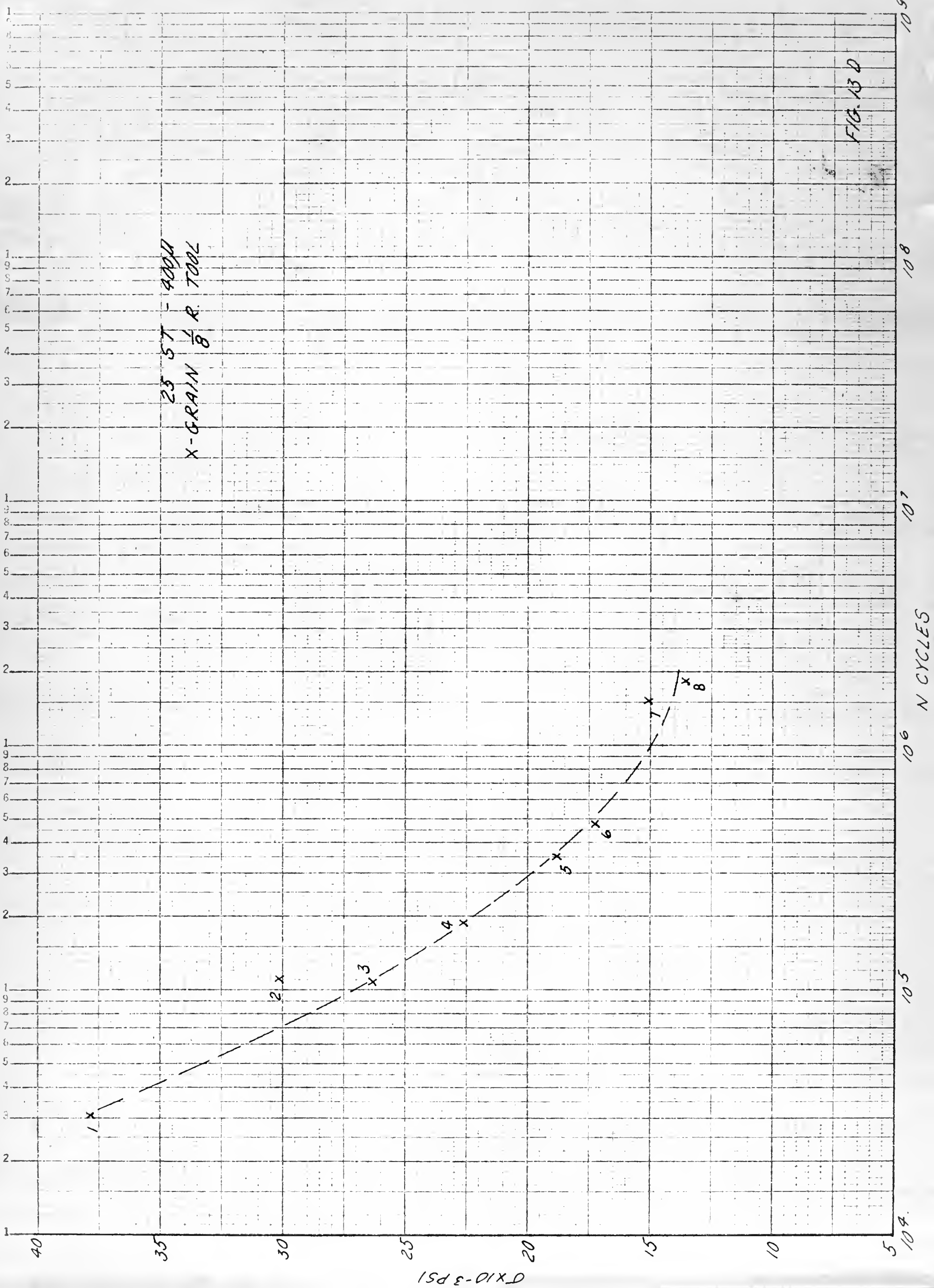


FIG. 13 D
X-GRAIN 1/8 R. TOOL
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5

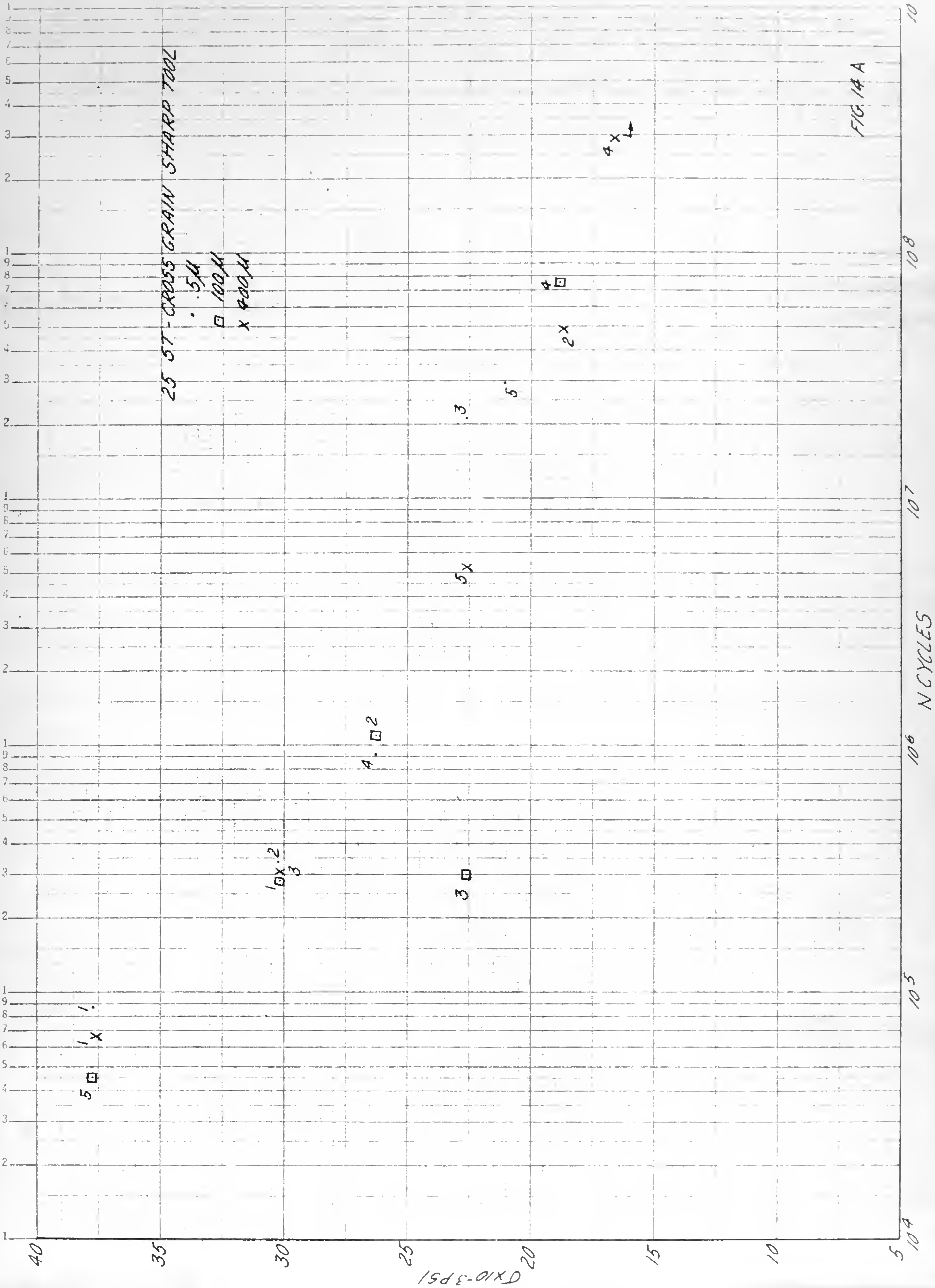

25 ST-CROSS GRAIN SHARP TOOL
. 5μ
□ 100μ
x 400μ
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

FIG. 14 A

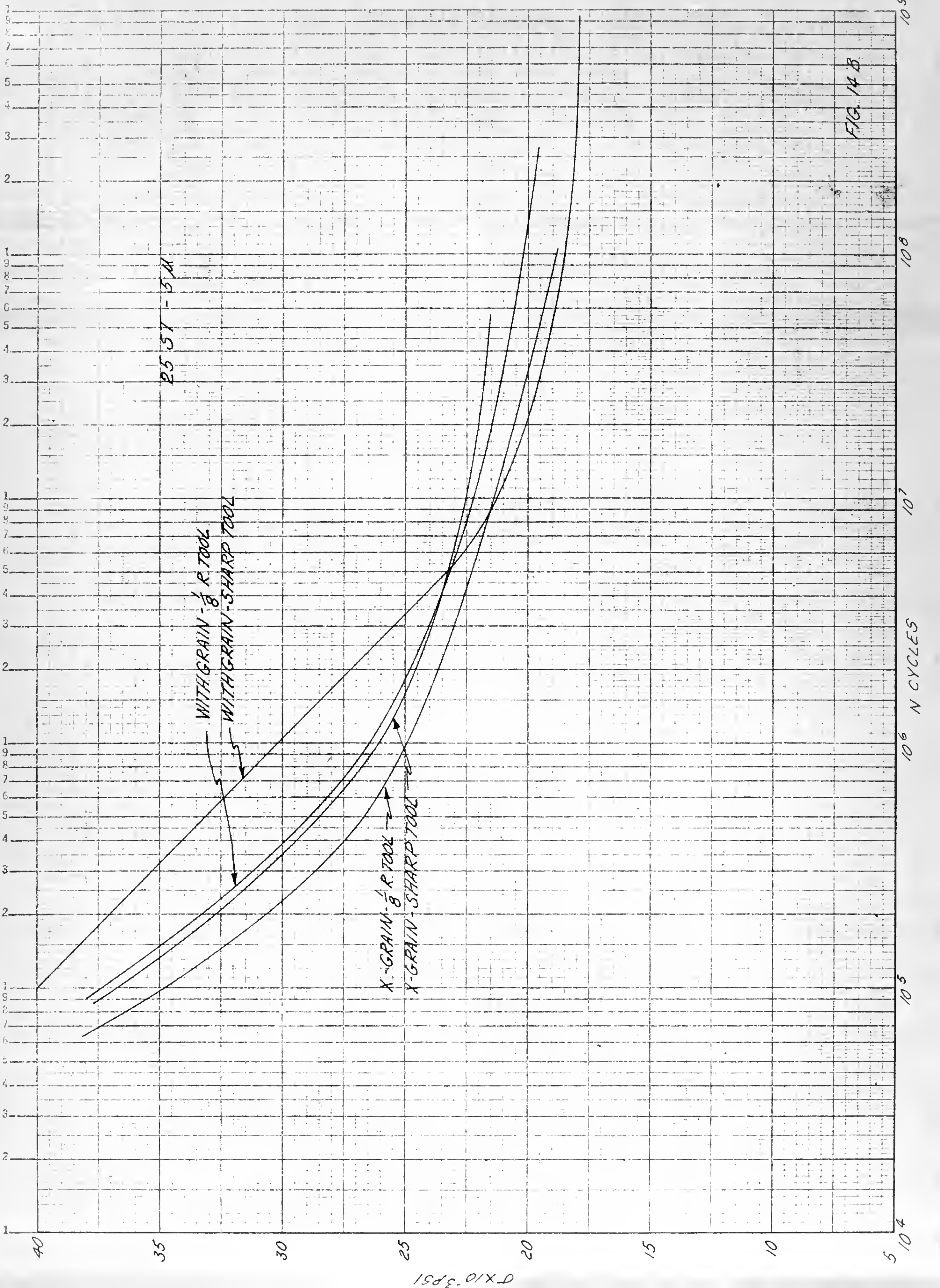


FIG. 14 B
25 ST - 3 M
WITH GRAIN - 1/8 R TOOL
WITH GRAIN - SHARP TOOL
X-GRAIN - 1/8 R TOOL
X-GRAIN - SHARP TOOL
N CYCLES
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5
$\sigma \times 10^{-3}$ PSI

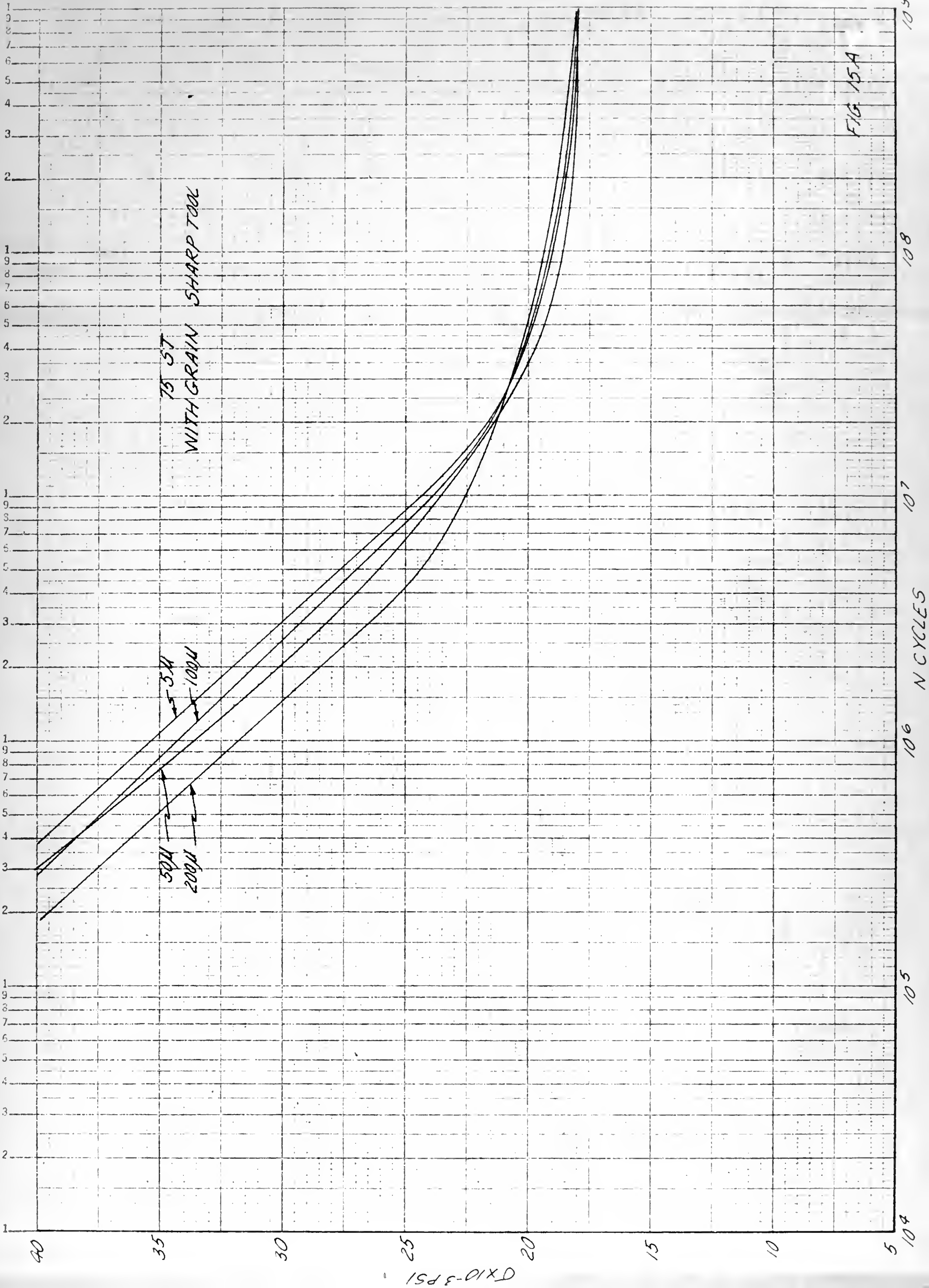
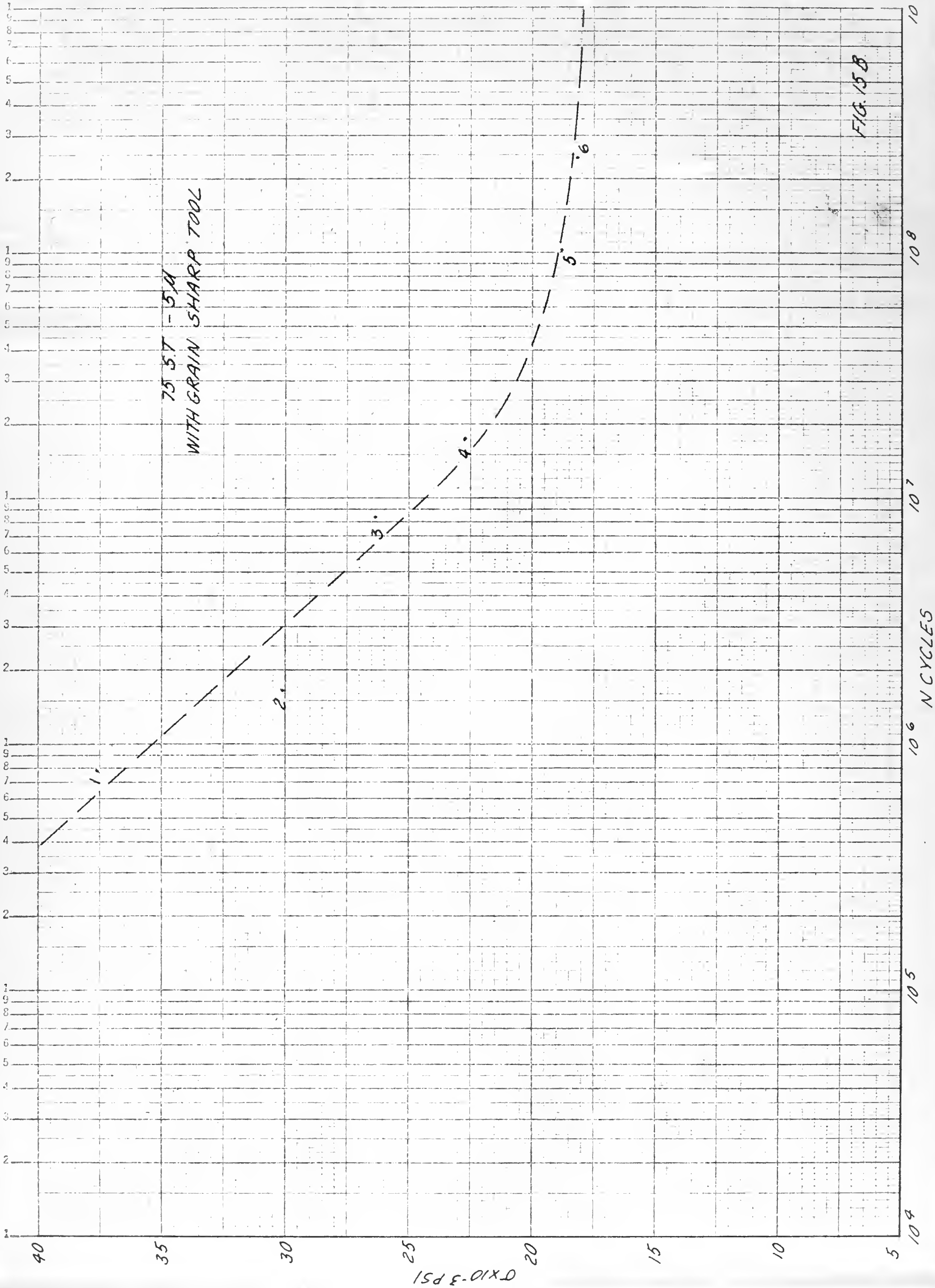


FIG 15A
75 ST
WITH GRAIN SHARP TOOL
5μ
100μ
50μ
200μ
N CYCLES
σ X10-3 PSI
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5


75 S.T. - 5A
WITH GRAIN SHARP TOOL
FIG. 15 B
N CYCLES
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5
σ x10^-3 PSI

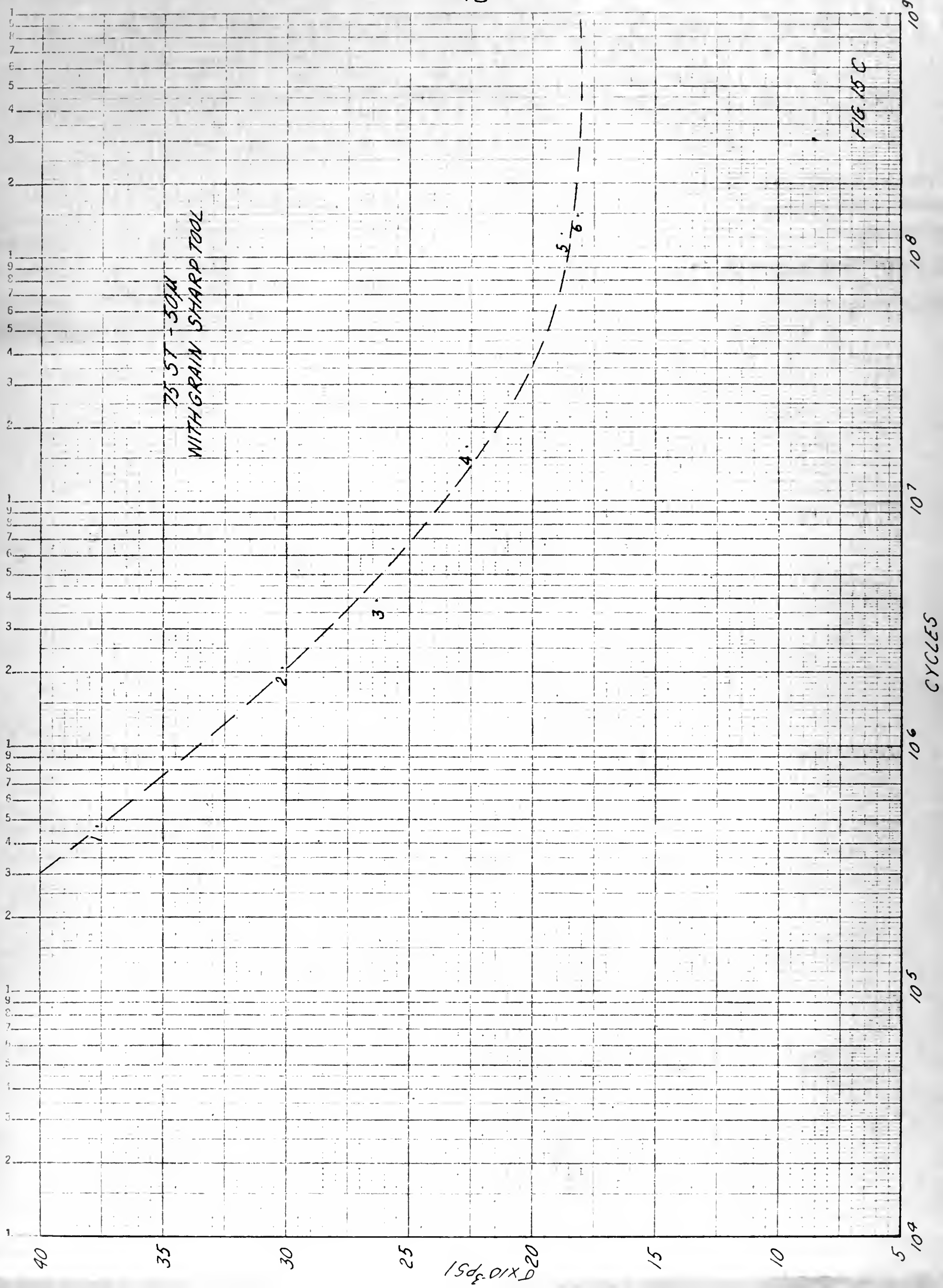
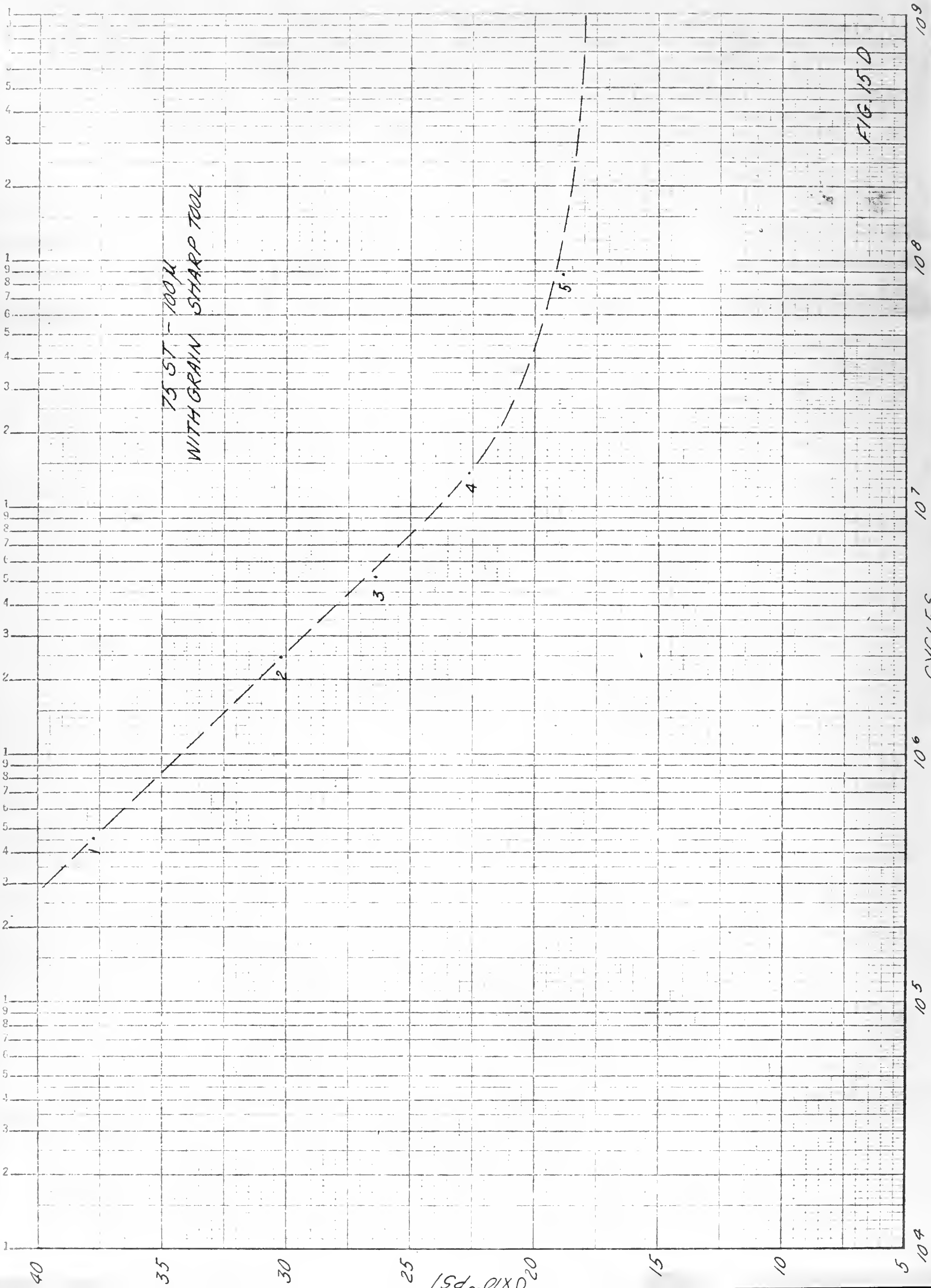
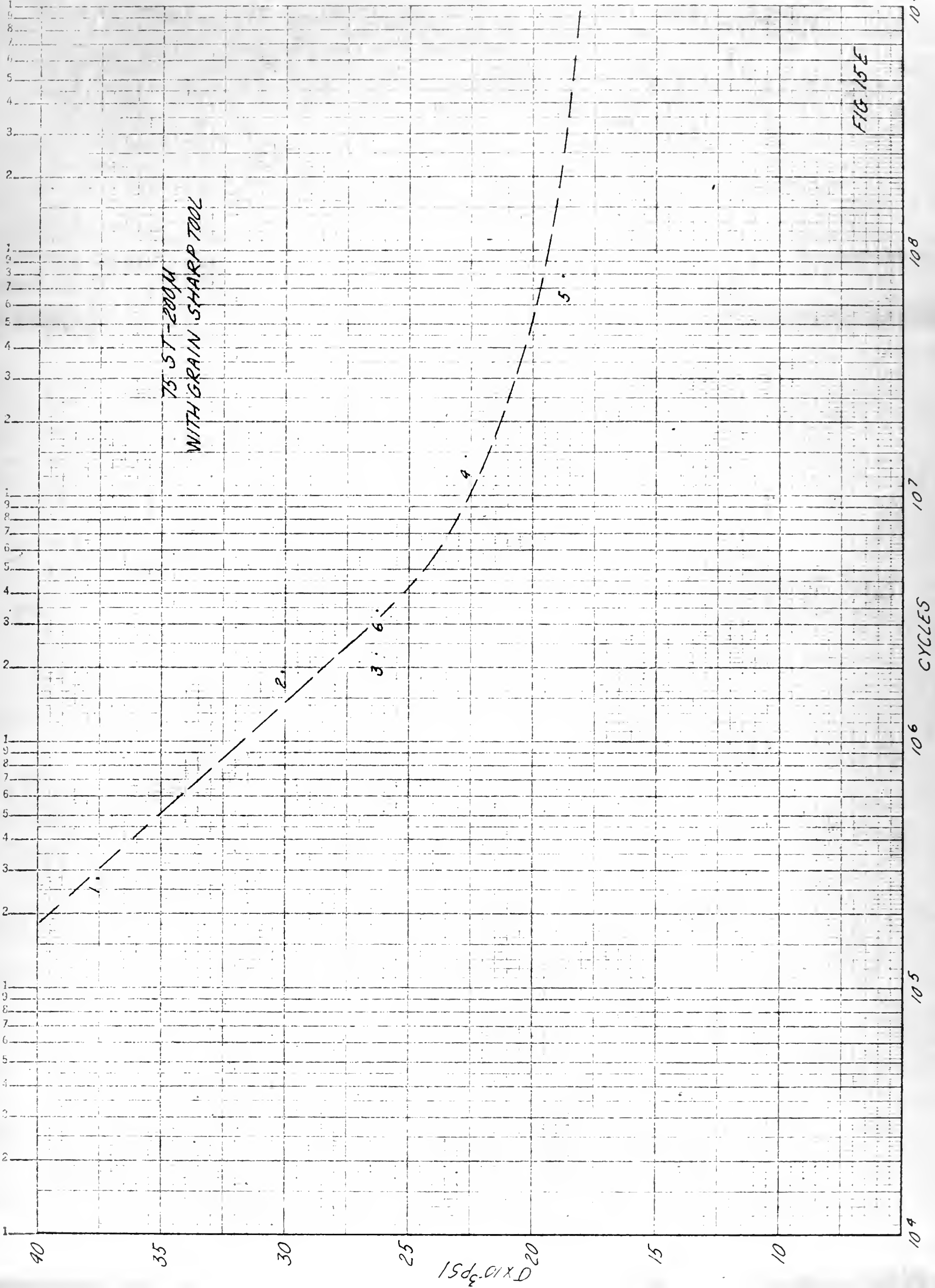


FIG. 15 C
75 ST - 30µ
WITH GRAIN SHARP TOOL
CYCLES
σ x10³ psi
40
35
30
25
20
15
10
5
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹


75 ST - 100μ
WITH GRAIN SHARP TOOL
FIG. 15 D
CYCLES
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9
1
2
3
4
5


75 ST-280M
WITH GRAIN SHARP TOOL
FIG 15E
CYCLES
$\sigma \times 10^{-3}$ psi
40
35
30
25
20
15
10
10^4
10^5
10^6
10^7
10^8
10^9

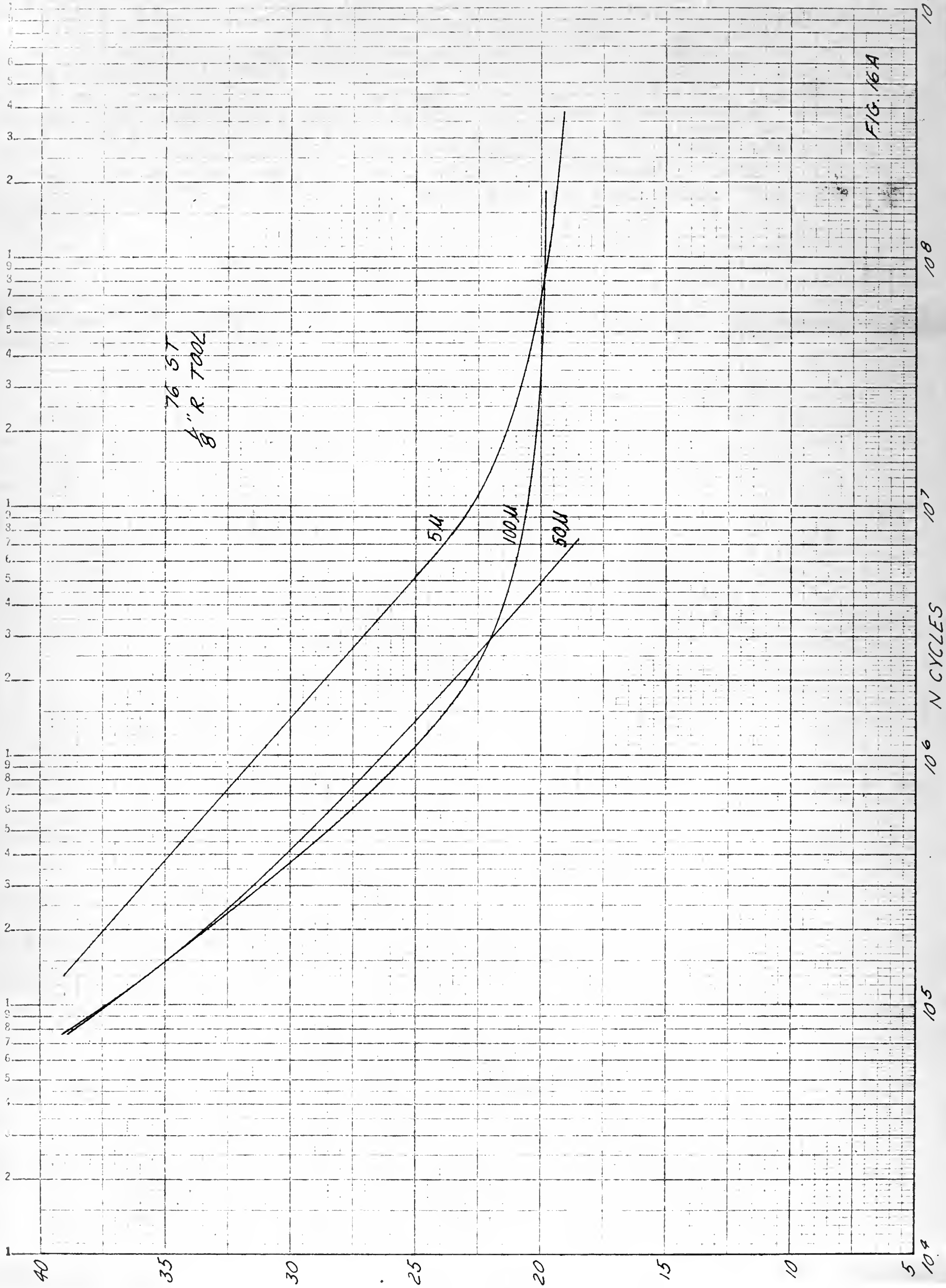


FIG. 16A
76 ST
1/8" R. TOOL
5M
100M
50M
N CYCLES
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5

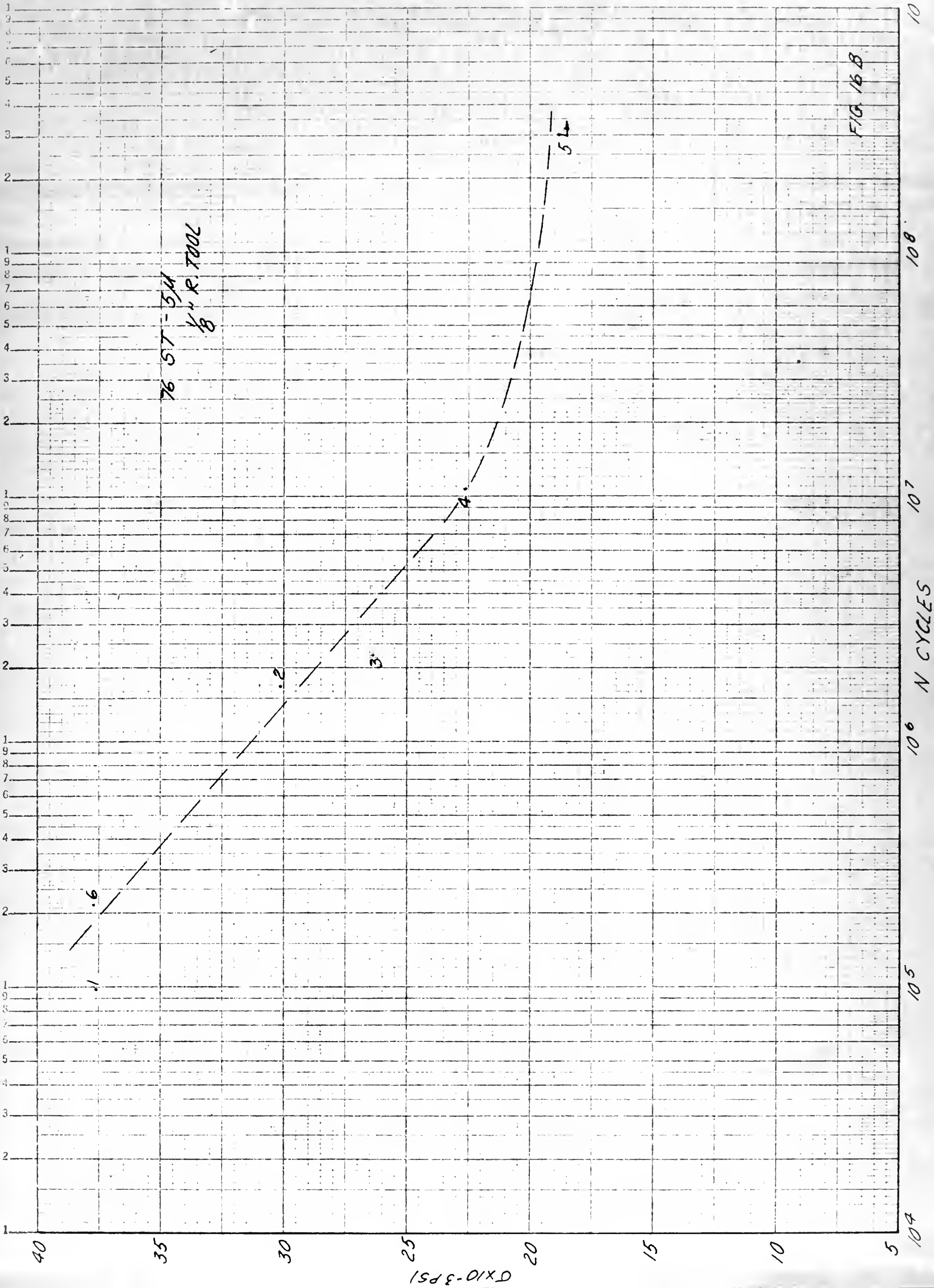


FIG 16B
76 ST - 5M
1/8" R. TOOL
N CYCLES
σ x10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

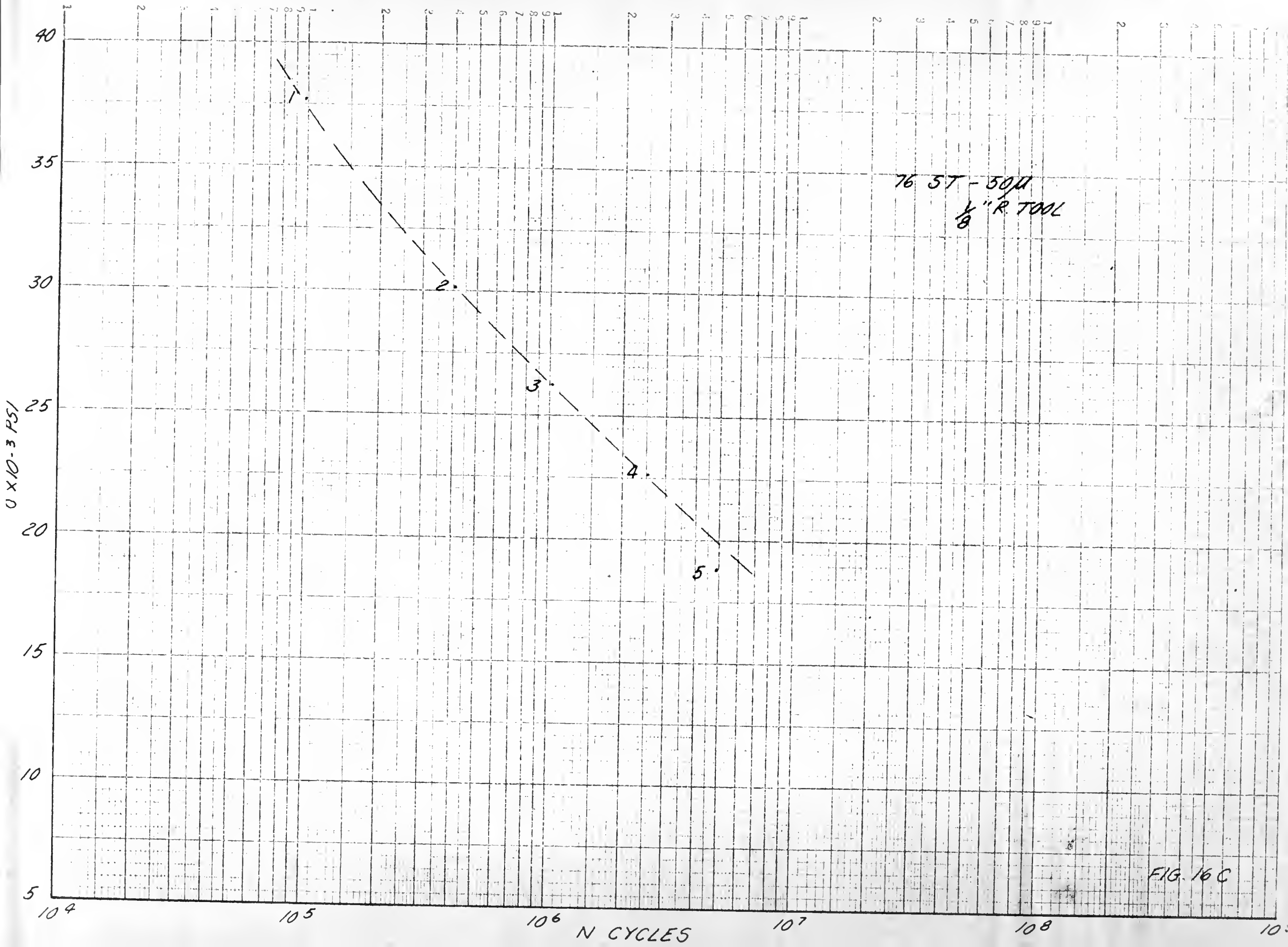

76 ST - 50M
1/8" R. TOOL
σ X10-3 PSI
40
35
30
25
20
15
10
5
N CYCLES
10^4
10^5
10^6
10^7
10^8
1
2
3
4
5

FIG. 16 C

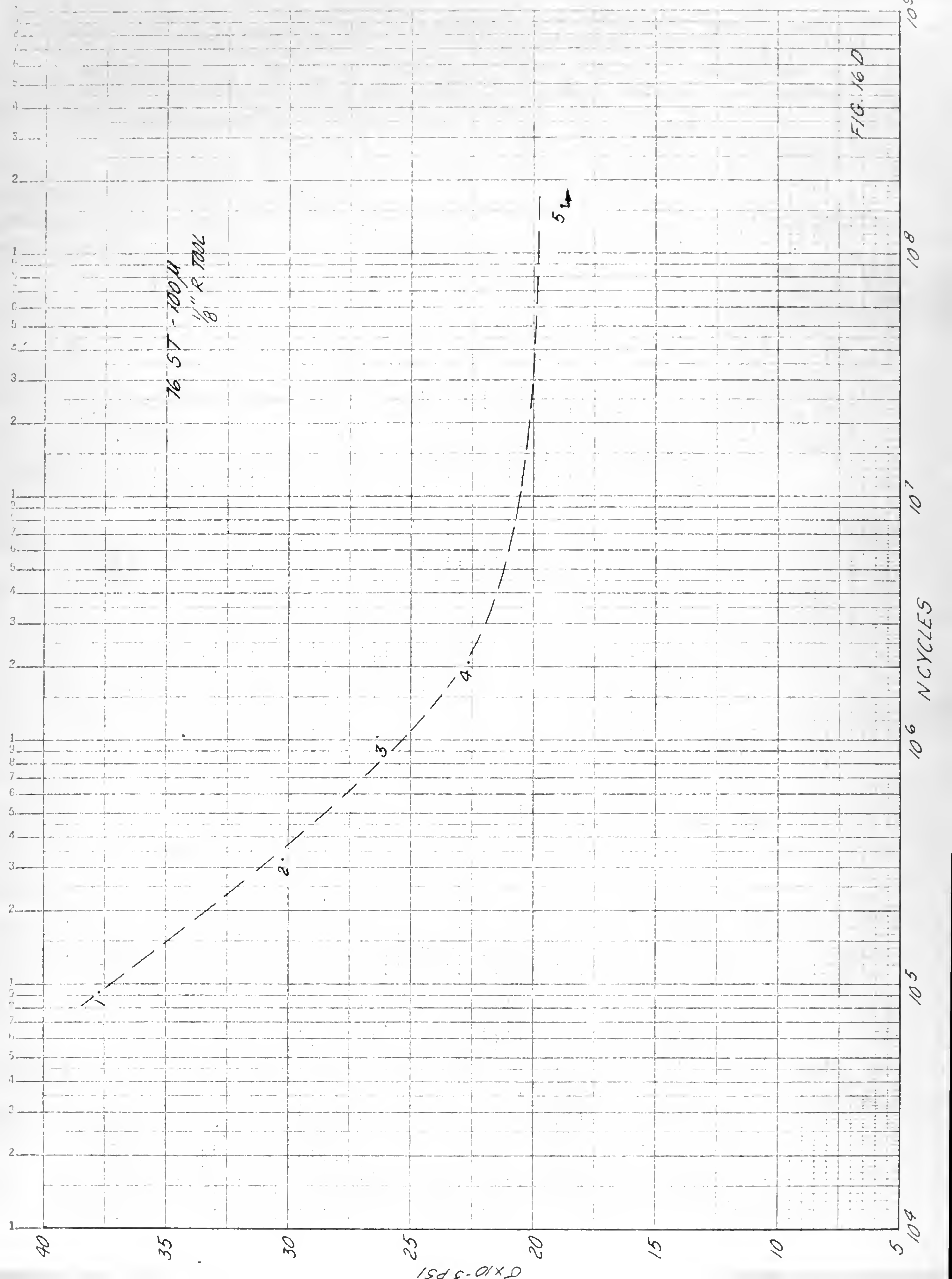


FIG 16 D
76 ST - 100 μ
1/8" R TOOL
N CYCLES
σ x10^-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

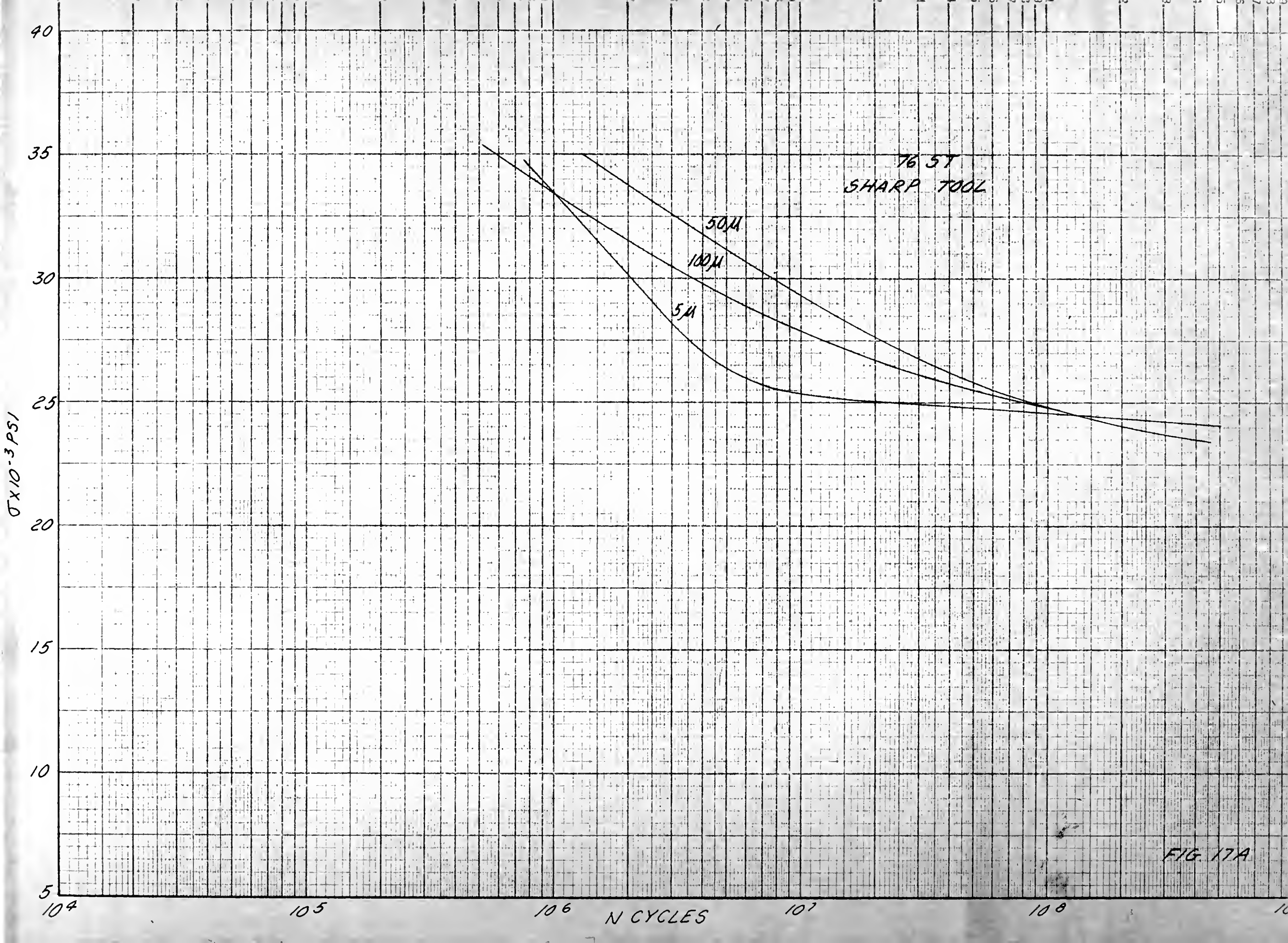

76 ST
SHARP TOOL
50μ
100μ
5μ
σ x 10^-3 PSI
N CYCLES
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8

FIG. 17A

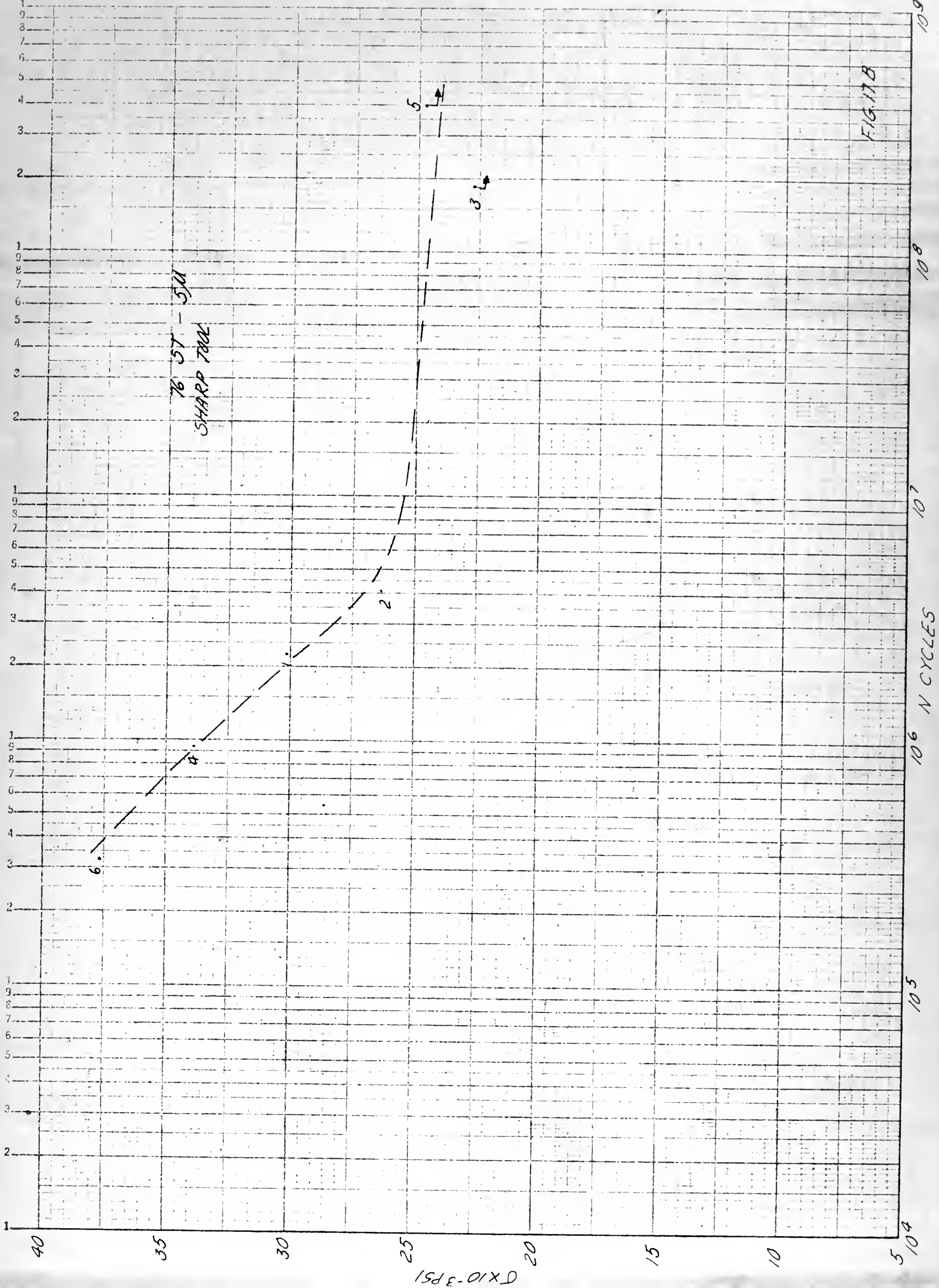


FIG. 17B
76 ST - 5M
SHARP TOOL
N CYCLES
σ x 10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9
1
2
3
4
5
6

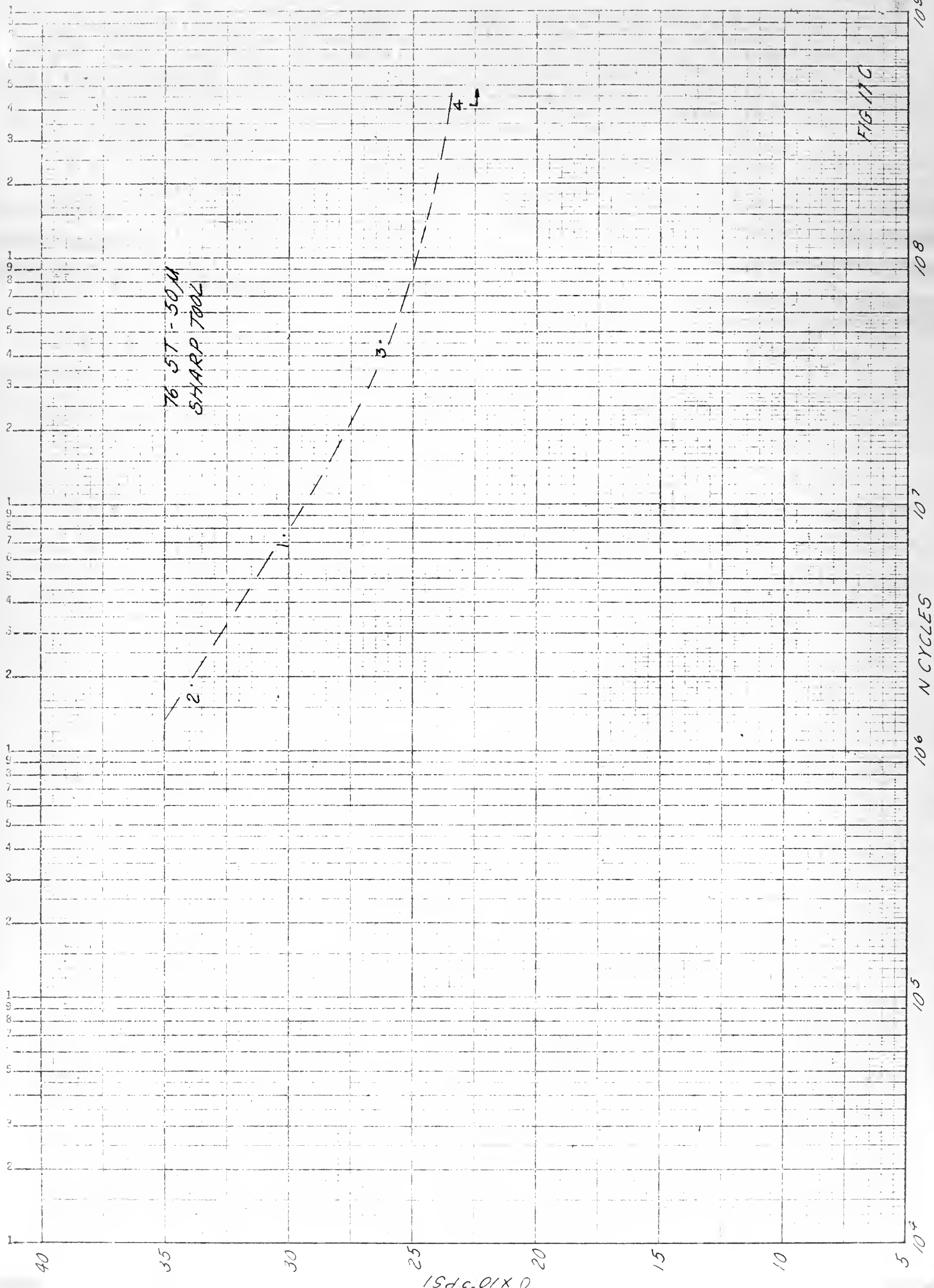


FIG 11C
76 ST - 30 M
SHARP TOOL
N CYCLES
40
35
30
25
20
15
10
5
1.
2.
3.
4.

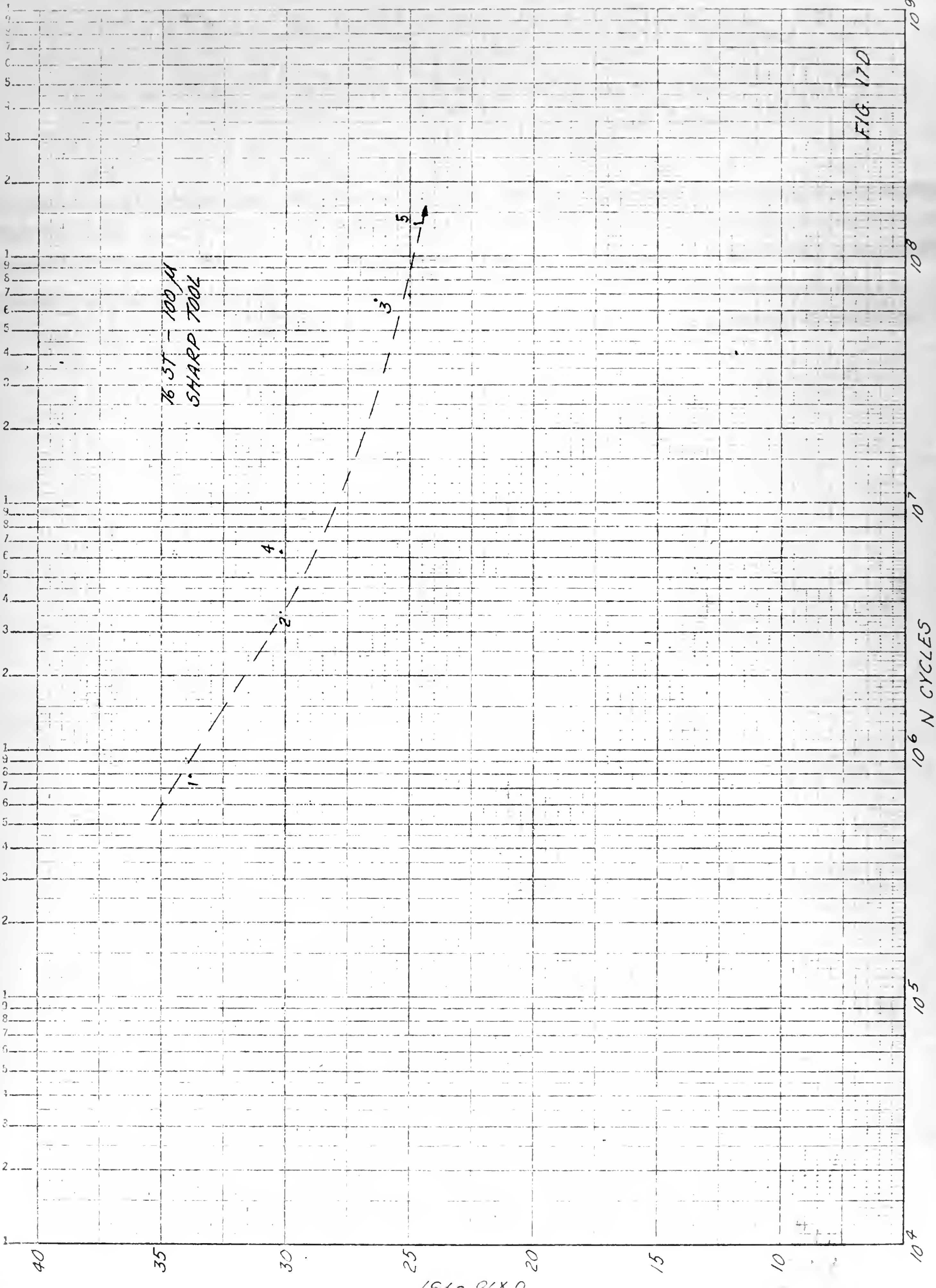


FIG. 17D
75 ST - 100 µ
SHARP TOOL
N CYCLES
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10

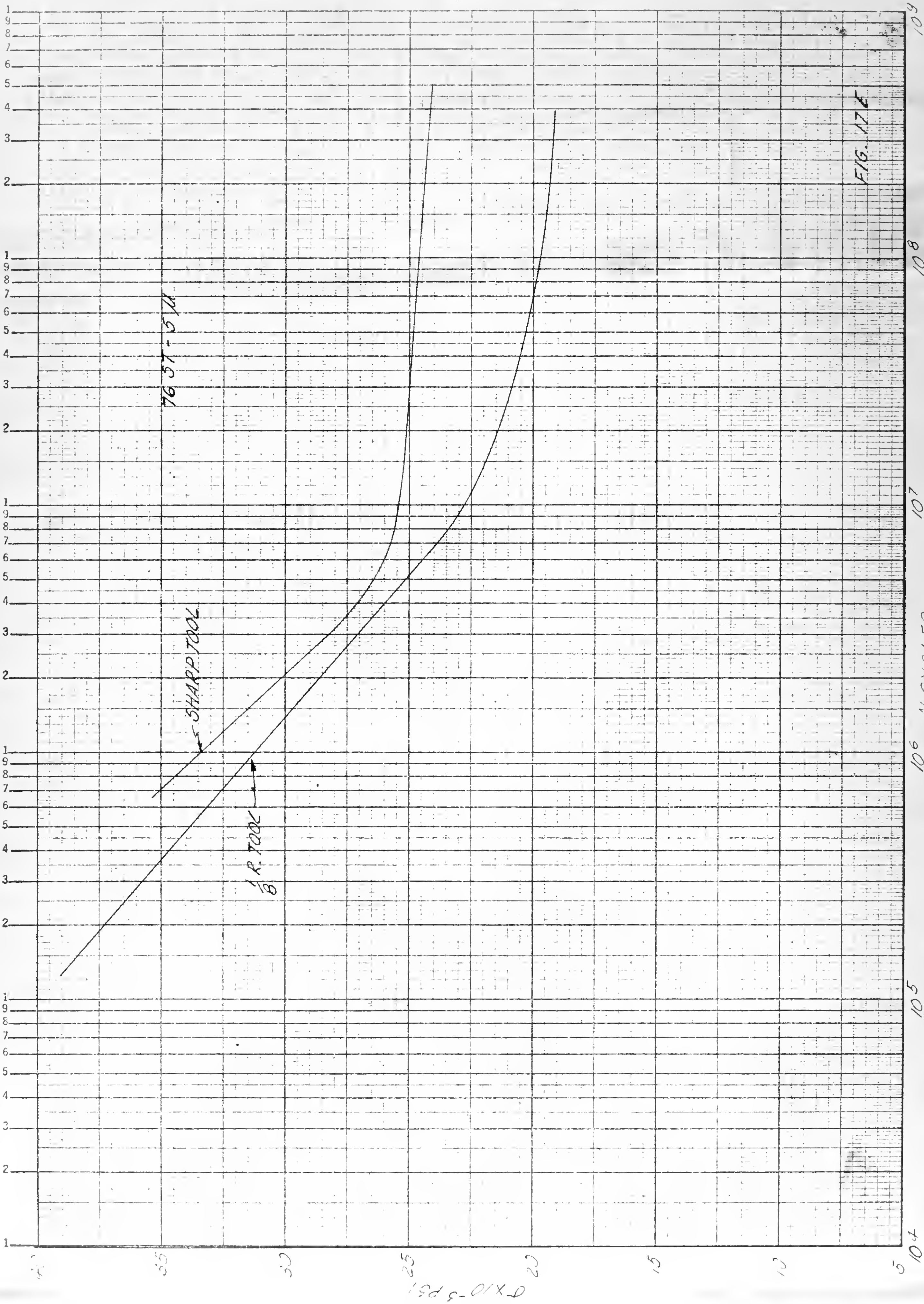
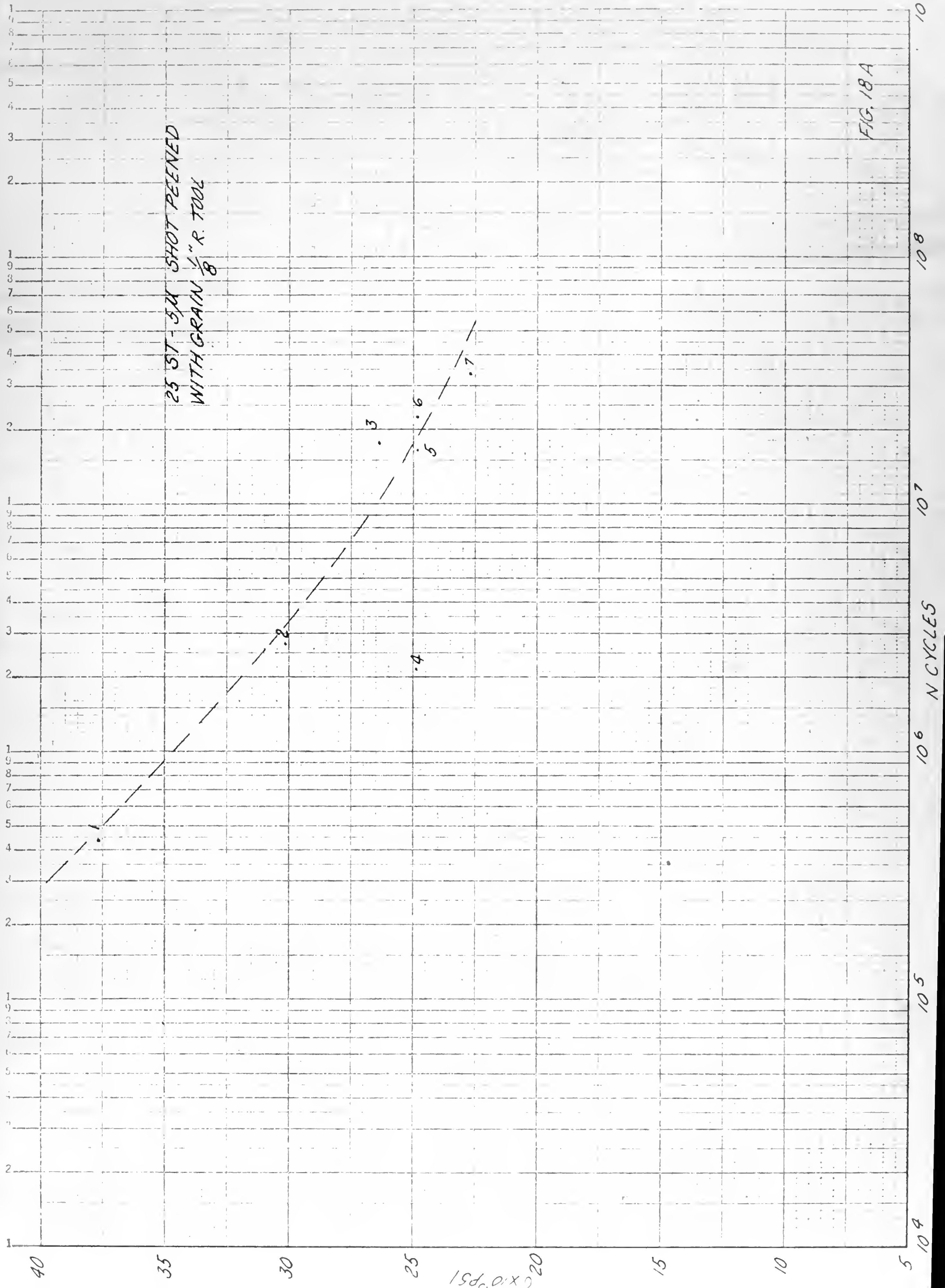


FIG. 17E
SHARP TOOL
1/8 R. TOOL
N CYCLES
σ X 10-3 PSI


25 ST-3M SHOT PEENED
WITH GRAIN 1/8" R. TOOL
FIG. 18A
N CYCLES
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

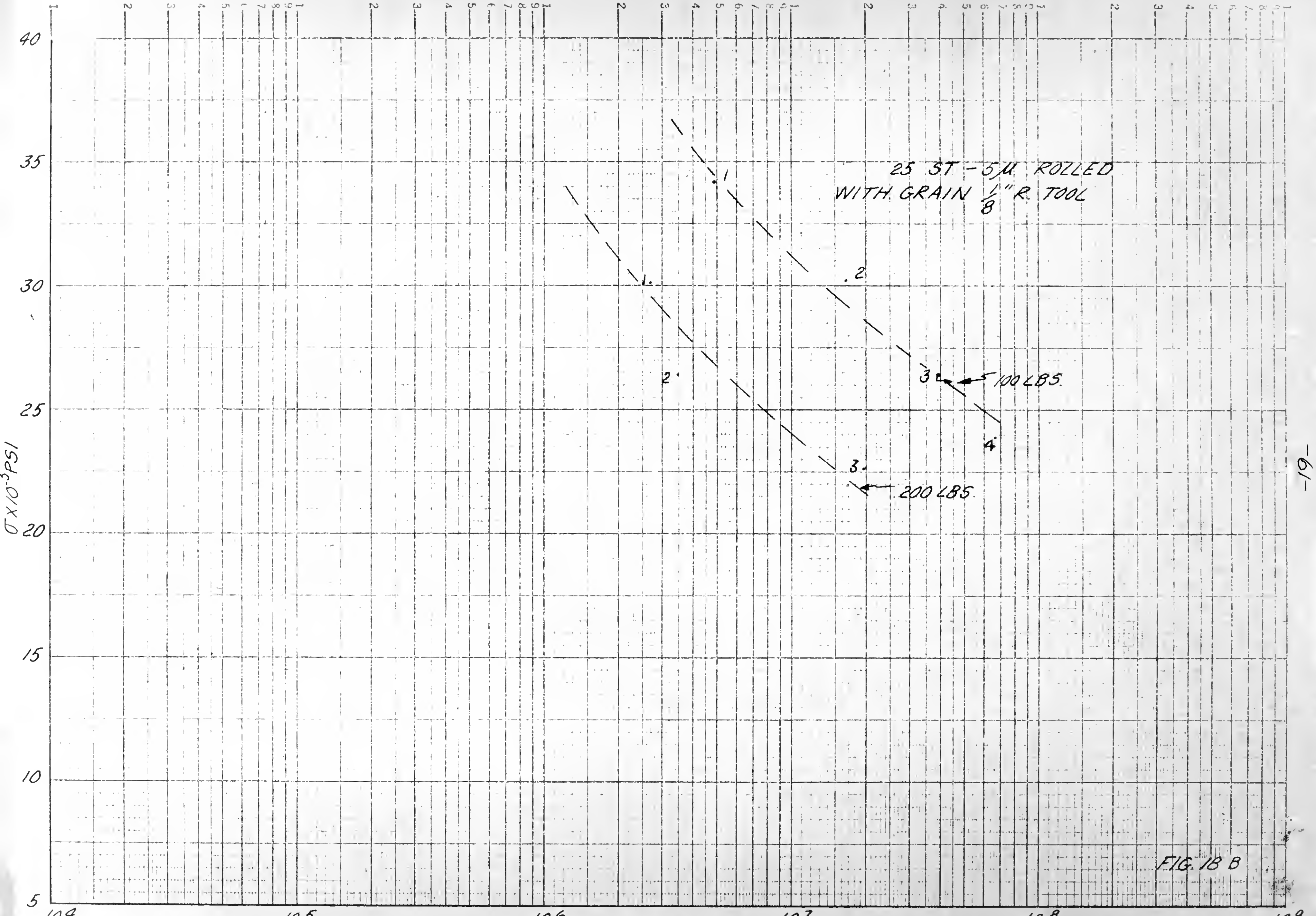

25 ST - 5M ROLLED
WITH GRAIN 1/8" R. TOOL
100 LBS.
200 LBS.
1
2
3
4
σ X 10⁻³ PSI
N CYCLES
40
35
30
25
20
15
10
5
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹

FIG. 18 B

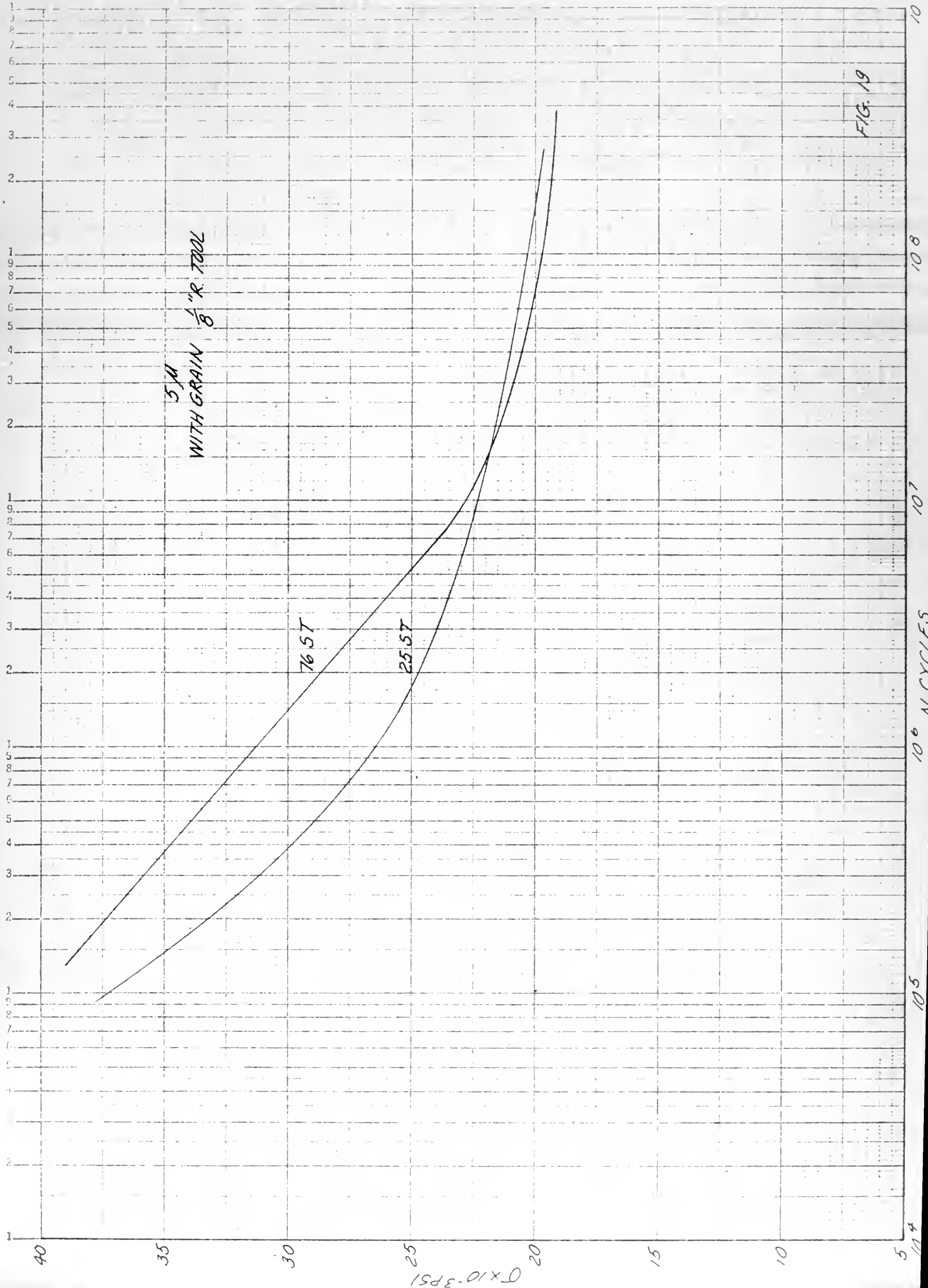


FIG. 19
5M
WITH GRAIN 1/8" R. TOOL
76 ST
25 ST
N CYCLES
σ×10-3 PSI
40
35
30
25
20
15
10
5
10^4
10^5
10^6
10^7
10^8
10^9

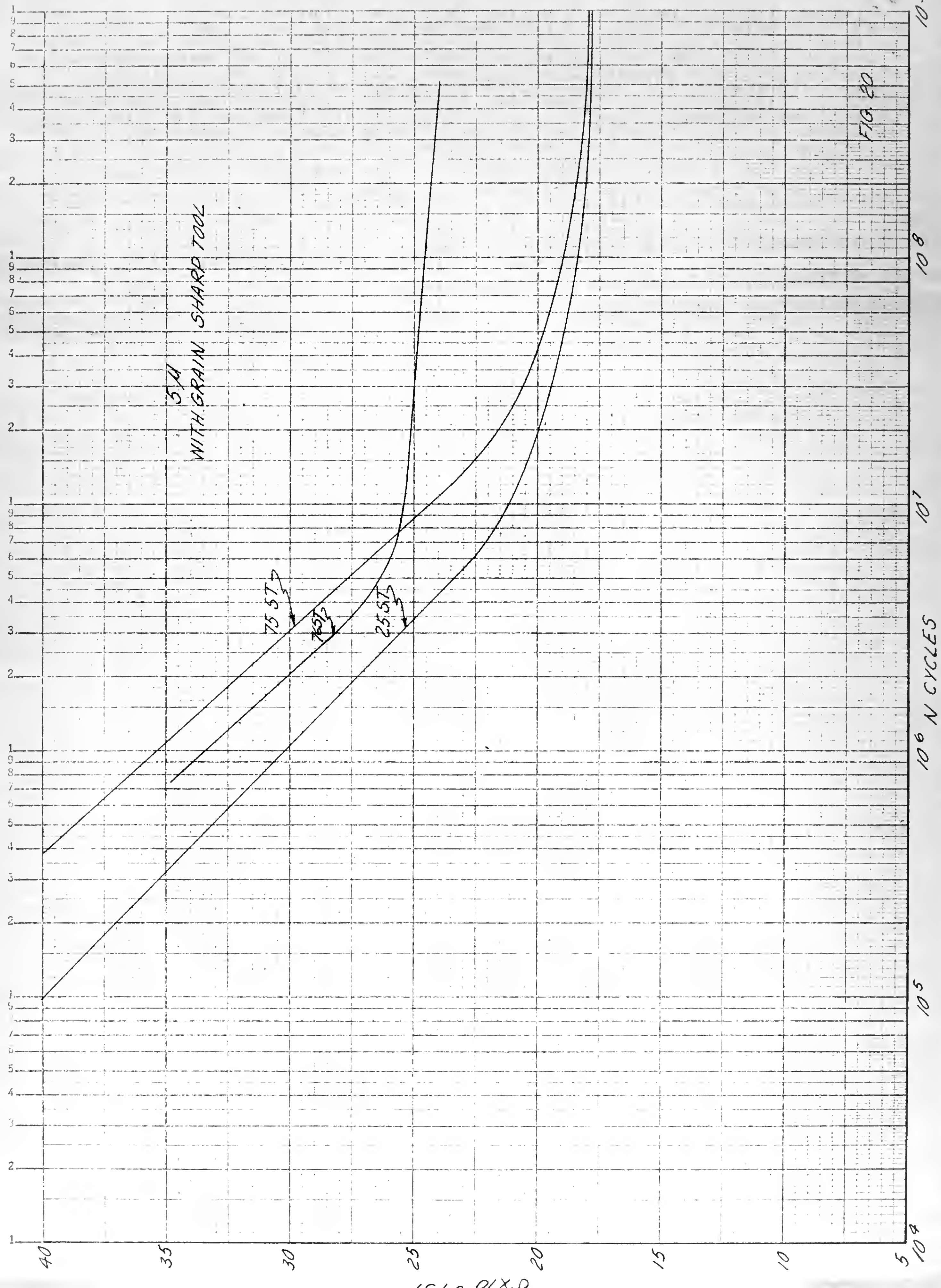
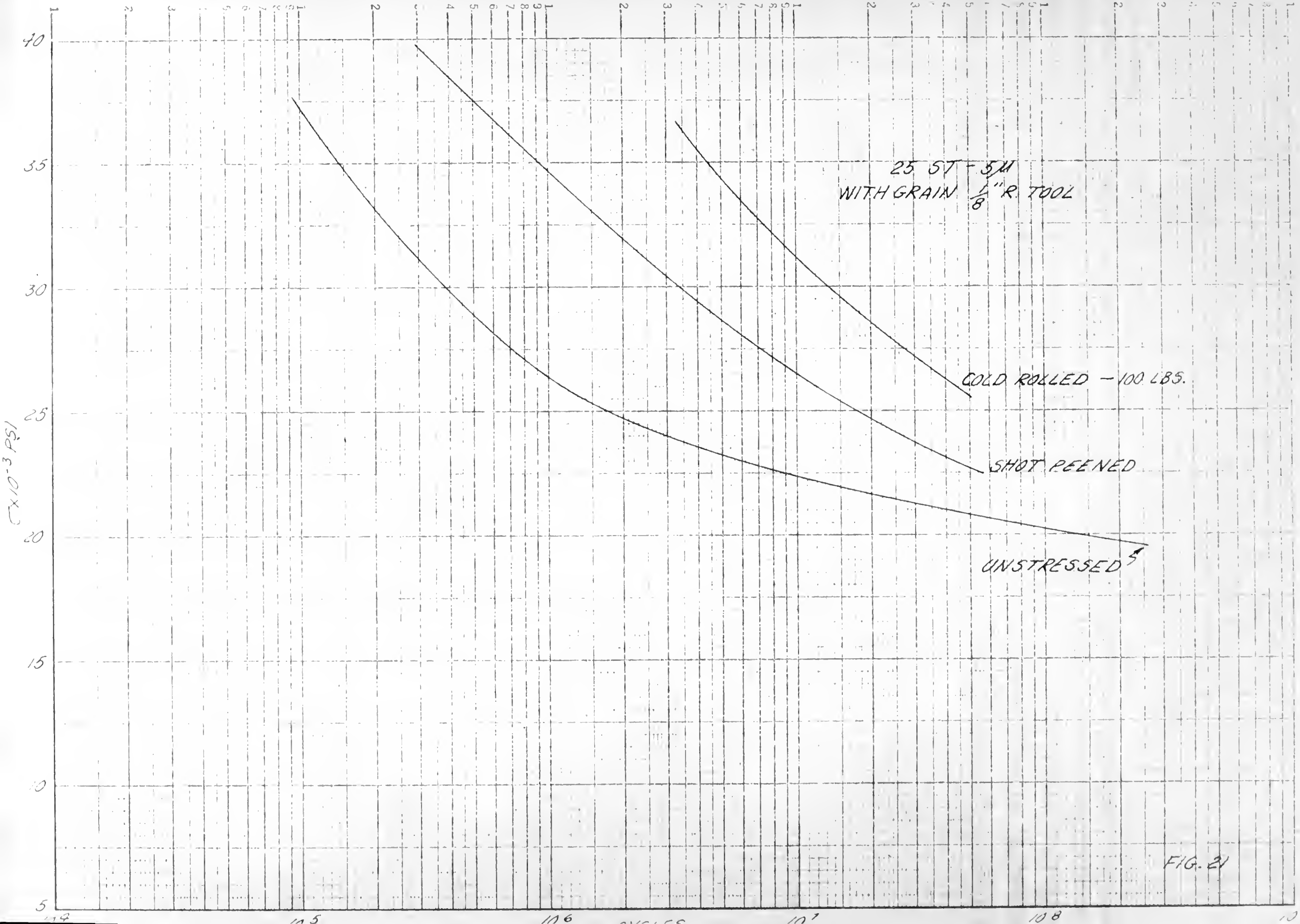


FIG. 20
5M
WITH GRAIN SHARP TOOL
75 ST
25 ST
N CYCLES
10^4
10^5
10^6
10^7
10^8
10^9
40
35
30
25
20
15
10
5


25 ST - 5M
WITH GRAIN 1/8" R. TOOL
COLD ROLLED - 100 LBS.
SHOT PEENED
UNSTRESSED
FIG. 21
40
35
30
25
20
15
10
5
$(\times 10^{-3}$ PSI)
10^5
10^6
10^7
10^8

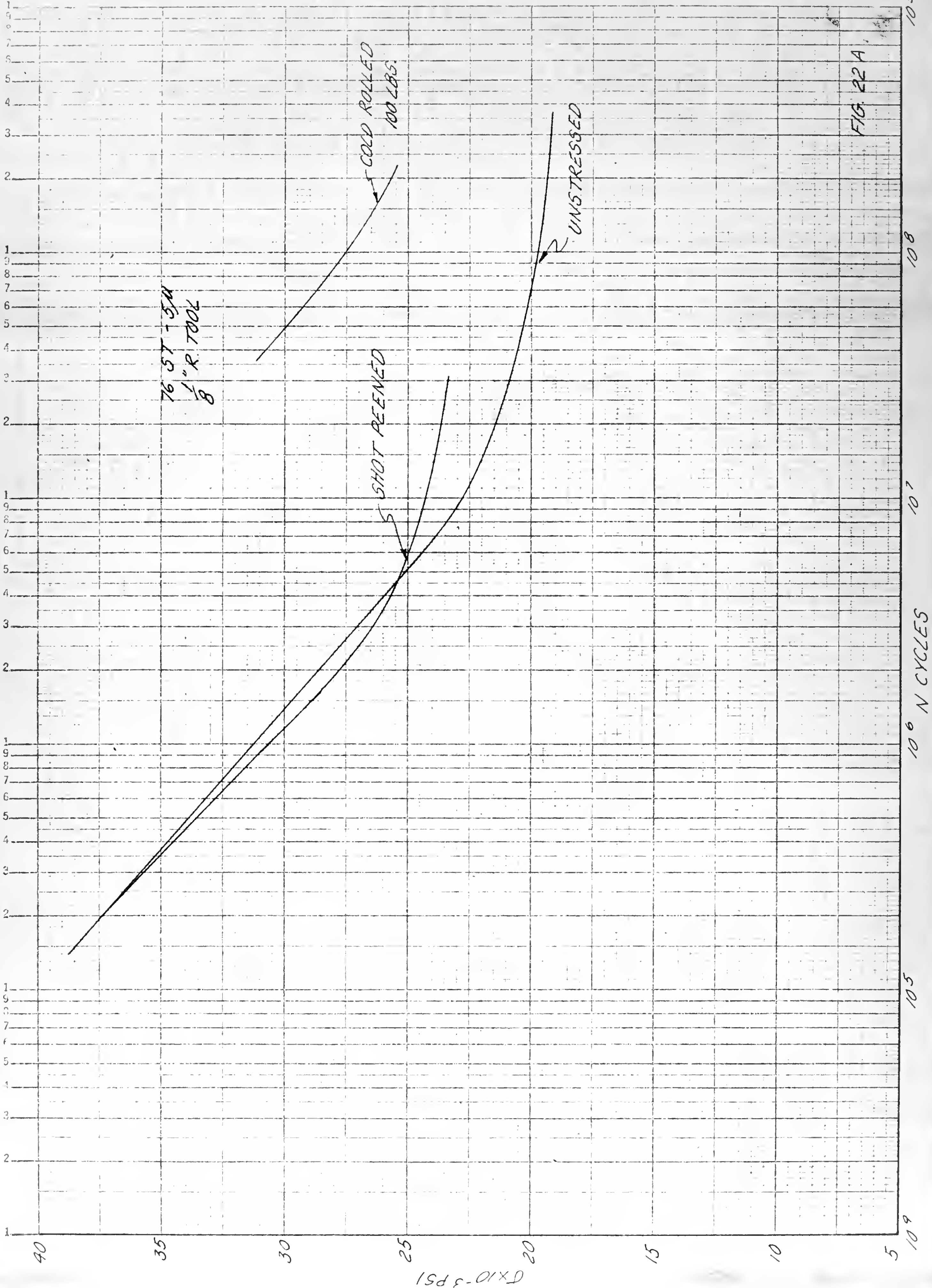

COLD ROLLED
100 LBS.
UNSTRESSED
SHOT PEENED
76 ST - 5N
1/8" R. TOOL
N CYCLES
σ x10^-3 PSI
40
35
30
25
20
15
10
5
10^5
10^6
10^7
10^8
10^9

FIG. 22 A

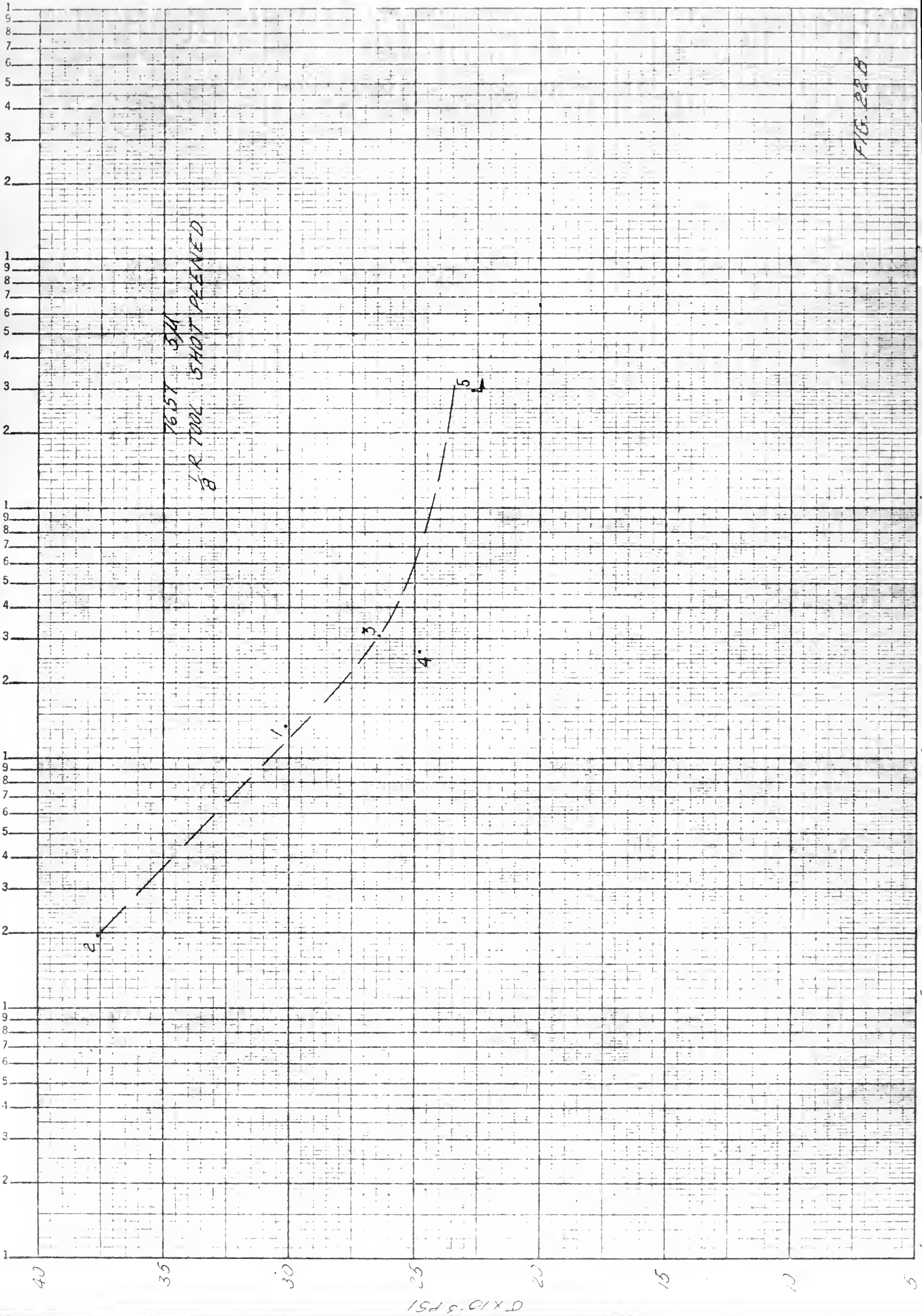


FIG. 22B
TEST 34
1/8 R TOOL SHOT PEENED
σ x 10-3 PSI
40
35
30
25
20
15
10
5

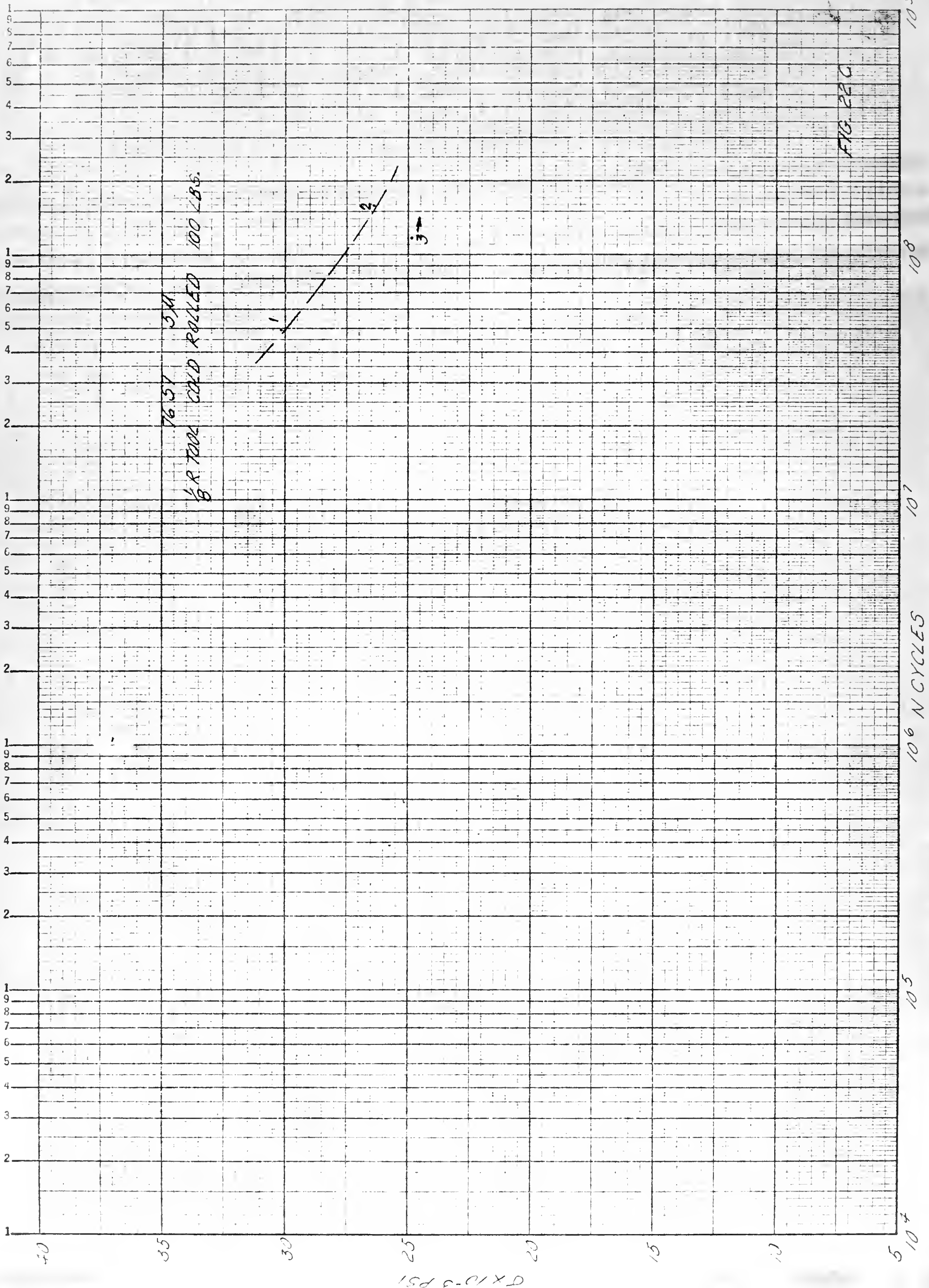


FIG. 22C
1/8 R TOOL 76.57 3Ω
COLD ROLLED 100 LBS.
N CYCLES
40
35
30
25
20
15
10
5

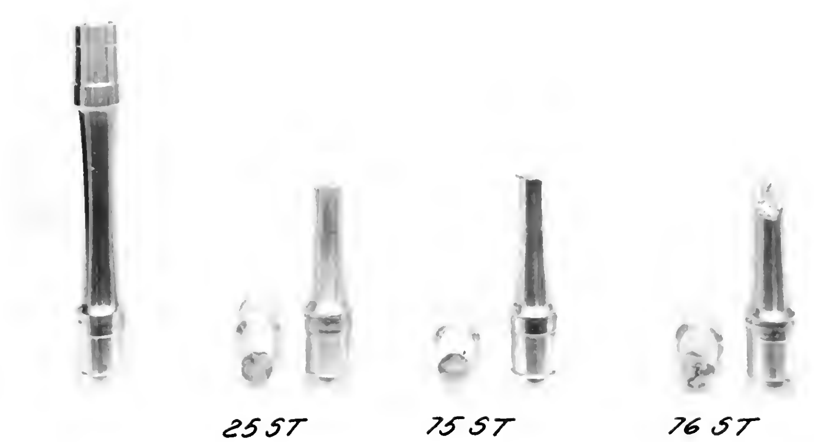


FIG. 23

TYPICAL FRACTURES